NASA/CR-2002-211249

Characterization of Subsystems for a WB-003 Single Stage Shuttle

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February 2002

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Prepared for Langley Research Center
under Contract NAS1-96013

February 2002

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Abstract

Subsystems for an all oxygen-hydrogen-single-stage shuttle are characterized for a vehicle designated WB-003. Features of the vehicle include all-electric actuation, fiber optics for information circuitry, fuel cells for power generation, and extensive use of composites for structure. The vehicle is sized for the delivery of a 25, 000 lb payload to a space station orbit without crew. When crew are being delivered they are carried in a module in the payload bay with escape and manual override capabilities. The underlying reason for undertaking this task is to provide a framework for the study of the operations costs of the newer shuttles.

Introduction

This document has been prepared to provide more detailed information on the subsystems required for a single-stage-rocket-powered shuttle vehicle. The information is needed in order to support a study of its operational aspects. For every new subsystem identified, background information is provided from the Shuttle subsystems. Although only partially reusable, the Shuttle is the only vehicle that is even remotely related to the fully reusable single stage vehicle that forms the basis for the current study of operations. In providing descriptions of the Shuttle subsystems, the operational differences between the old and conceptual shuttles can be used to better evaluate operational costs of the latter.

The basic information for the study consists of a subsystem narrative and a CONSIZ Level III mass properties printout for a vehicle designated WB-003. These documents were used as guidelines for this study and are included as Appendices A and B. The weights and power requirements for a manned module that might be used on space station personnel change-out missions are identified in Appendix C. This appendix is included in order to provide a basis for operations studies that might involve manned flight. Summary structure mass properties (centered around unit weights) are provided in Appendix D. The tables in Appendix D provide details of the data given relative to structure in each section of the text. The salient characteristics of the vehicle are as follows:

Reference length: 212.94 ft
Payload Delivery capability: 25,000 lb of payload up to 35 ft in length to the International Space Station
Propulsion: 7 High Pressure LOX/LH bell engines
Mission Mode: Vertical launch and horizontal landing

In the following pages, subsystem characteristics, such as weight, size, power, accessibility, and maintainability are given. Information regarding location, envelope, weight, number of line replaceable units (LRU) is also included. Not all of the characteristics are identified for all of the subsystems. The items listed are merely examples of data supplied. Some of the information provided (particularly that related to structure) must be regarded as the result of conceptualizing, but is given in order to provide a framework for a study of operations. Structural non-optimums and LRU installation penalties are assigned based on a combination of historical data and other estimating techniques. In regard to primary structure, thicknesses of materials are assigned that will give the approximate weights shown for the structural areas assigned.

Honeycomb sandwich is used for most of the structure in this vehicle. For purposes of modeling, 0.006-in. thick plies of graphitic woven material (in multiple layers) are used for face sheets and the resin changed as required from a polyimide to a polyamide depending on expected service temperature. A honeycomb core having a polyamide base is good for service to about 350°F. The honeycomb is manufactured by dipping a honeycomb made of a cardboard material into a polyamide resin. This honeycomb would be used when graphite-epoxy structure is called for.

A honeycomb fabricated using a fiberglass-reinforced polyimide base is good to about 500°F (for continuous use) and up to 700°F for short-term service. This core is used when a graphite-polyimide structure is called for. A closed-cell-rigid-imide foam is used when low conductivity is required. Otherwise, the core is not foam filled. All core densities are 4 lb/ ft^3. With the exception of the main engine thrust cone for which core density was increased to 6.5 lb/ft^3.

In modeling the structure, the weights given by the CONSIZ program are first downsized to allow for an estimated percentage for non-opts, a number that is estimated to be appropriate for the particular structural element. Once the downsized weight is obtained, the number of face-sheet plies and core thicknesses and densities are varied in order to target the downsized CONSIZ weights. For all honeycomb sandwiches, 0.06 lb/ft^2 is allowed for bonding agent. Background weights from the Shuttle program and modelled weights for the WB-003 vehicle are shown in Appendix D.

In regard to the annotation of the text, figures, and tables; the mass properties codes employed in the Shuttle program have been adopted and expanded upon. For example, the wing is given the code '1.0', the tail '2.0', the body group '3.0' etc. These same codes are assigned to the text related to the same subject matter. In addition, references are given the same code as the subject matter to which they apply, such that the wing references are coded 1.1, 1.2, etc. References are placed at the end of each section. Figures are also numbered as 1.0, 1.1, 1.2 etc. An exception to the "Code Rule" is the use of Code 70.0. This code is used for a discussion of servicing and maintenance aspects of the WB-003 vehicle. Codes 15 through 69 are reserved for such items as personnel and payload provisions when needed.

Nomenclature

ACC	Advanced carbon composite
AFRSI	Advanced flexible reusable surface insulation, usable up to 1200°F
Al-Li	Aluminum-lithium
APU	Auxiliary power unit
CONSIZ	CONfiguration and SIZing Program
EMA	Electro-mechanical actuator
FADS	Flush air data system
FRSI	Flexible reusable surface insulation, usable up to 700°F
Gr-Ep	Graphite epoxy
Gr-Pi	Graphite-polyimide
He	Helium
HIP	Hot isostatic pressing
HRSI	High temperature reusable surface insulation
IHOT	Integrated hydrogen/oxygen technology
IVHM	Integrated vehicle health monitoring
LCD	Liquid crystal display
LH	Liquid hydrogen

LOX	Liquid oxygen
LRU	Line replaceable unit
MDM	Multiplexer-demultiplexer
MMH	Monomethyl hydrazine
N_2O_4	Nitrogen tetroxide
PEEK	Polyetheretherketone
Non opts	Secondary structure and accessories
N.O.F.	Non optimum factor, all-up weight divided by basic structure or system weight
OMS	Orbital maneuvering system
Pa/C	Polyamide cardboard honeycomb
PDU	Power drive unit
Pi/G	Polyimide glass honeycomb
PMI	Polymethacrylimide foam
P/L	Payload
PVD	Purge, vent, and drain system
RCC	Reusable carbon composite
RCS	Reaction control system
RLV	Reusable launch vehicle
RTLS	Return-to-launch-site
RTV	Room temperature vulcanizing adhesive
SEADS	Shuttle entry air data system
SIP	Strain isolation pad
SSME	Space Shuttle main engine
TABI	Tailored advanced blanket insulation
TPS	Thermal protection system

1.0 Wing Group

Shuttle Background

In the current Shuttle mass properties documents, the weight of the landing gear doors and attach points, elevon hinges, and wing-to-body fairings are all charged to the wing. The wing at its root is a modified NACA 0010-64 airfoil (Ref. 1.1). The wing gradually changes from a 10% thickness to 12% at its tip. The wing is thickened near its root in order to accommodate the landing gear rendering the 10% root chord no longer a real NACA airfoil. The wing sections are gradually transformed to the 12% airfoil section from root to tip in order to a give greater leading edge radius near the tip for thermal reasons. The wing leading edge, near its root, is faired into the fuselage with a large glove.

The Shuttle exposed wing planform is 1922 ft^2. The maximum root-chord-outer-moldline thickness is approximately 5 ft. The interior height is approximately 4 ft. The wing is fabricated principally from aluminum. Wing covers are of conventional skin-stringer construction over the wing torque box section. This section extends from the aft spar to a spar just to the rear of the main gear well. Aluminum honeycomb sandwich covers are used outboard and forward of the main gear well. Ribs are of open truss construction having aluminum tubing for diagonal bracing in the plane of the rib. The four major spars in the wing are of corrugated aluminum design – the corrugations providing a means for alleviating strains that might be induced by thermal gradients. The wing leading edge spar on the Columbia (Orbiter 102) is of honeycomb sandwich construction. The leading edge spars on subsequent Shuttles (nos. 104-106) are configured with corrugated webs and hat section caps.

Half ribs are used midway between major (full) ribs in order to reduce wing panel deflection. This was done in order to reduce the tendency for any Shuttle tile to become detached. The half ribs extend over only a fraction of the depth of the airfoil cross-section. The Shuttle wing unit weight is 8.4 lb/ft^2. This is based on the 1,922 ft^2 listed above and an exposed wing weight of 16,235 lb from a Rockwell International (internal) mass properties report for the Shuttle Orbiter dated July 2, 1995. The Shuttle wing carry-thru is integral with the body structure and a weight for the carry-thru function is therefore not identifiable, but is estimated to be about 600 lb.

WB-003 Concepts

The WB-003 wing is of a clipped-delta planform having NACA 0010-64 airfoil (Ref. 1.1). The root chord is 58 ft, tip chord is 22 ft, and semi-exposed-span is 30 ft. The wing exposed planform area is 2580 ft^2 (appendix B).The wing covers, ribs, and spars are all fabricated from graphite-polyimide (Gr-Pi) honeycomb sandwich. The honeycomb face sheets are modeled using 0.006 inch Gr-Pi plies, 17 plies at the wing root tapering to 5 plies at the wing tip. The polyimide honeycomb core is 3 in. thick at the wing root tapering to 1/2 in. at wing tip. The wing is configured with five ribs and two spars. Ribs and spars are also fabricated from Gr-Pi honeycomb sandwich. A Gr-Ep structural box behind the LOX tank, and just below the engine compartment, acts as a carry-through for the wing structure. Based on exposed wing planform, the WB-003 wing has a unit weight of 6.2 lb/ft^2. The exposed wing weight is based on the first two items in Table 1 below and a 2580 ft^2 area.

Table 1. Wing Weights

Item	Wt, lb
Basic wing weight (Exposed planform 2,580 ft^2)	12,282
Non opts (N.O.F. = 1.3)	3,684
Fairings (Area = 626 ft^2)	2,337
Carry-through (2 beams, YZ plane, area = 256 ft^2)	3,235
Wing total	21,538

The polyimide resin used in the wing construction is a thermoset. Its service temperature is about 600°F. Gr-Pi (especially composite PMR-15) shows greater toughness than most epoxies and thus is less sensitive to stress concentrations due to flaws or impact damage (Refs. 1.2 , 1.3, and 1.4). However, some degradation occurs at elevated humidities and temperatures (Ref. 1.5).

From the standpoint of accessibility, the outer moldline wing at maximum thickness is 6.7 ft at the wing root and 2.6 ft at the wing tip. Intermediate full ribs are located at stations y = 269 and y = 471 (Figs. 1.0 and 1.1). Crawl space height near maximum airfoil thickness (i.e. @ 40% chord) and near the inboard intermediate rib is approximately 5 ft. Crawl space height at the outboard intermediate rib near max chord is approximately 3 ft. One quad-redundant electro-mechanical actuator is mounted on each intermediate rib; these actuators operate the inboard and outboard elevons respectively. With allowance for structure and thermal protection, crawl space at the inboard elevon actuator is estimated as 3 ft and, at the outboard elevon location, as 2 ft. These figures are somewhat lower than the max chord values because of tapering of the airfoil section toward leading and trailing edges.

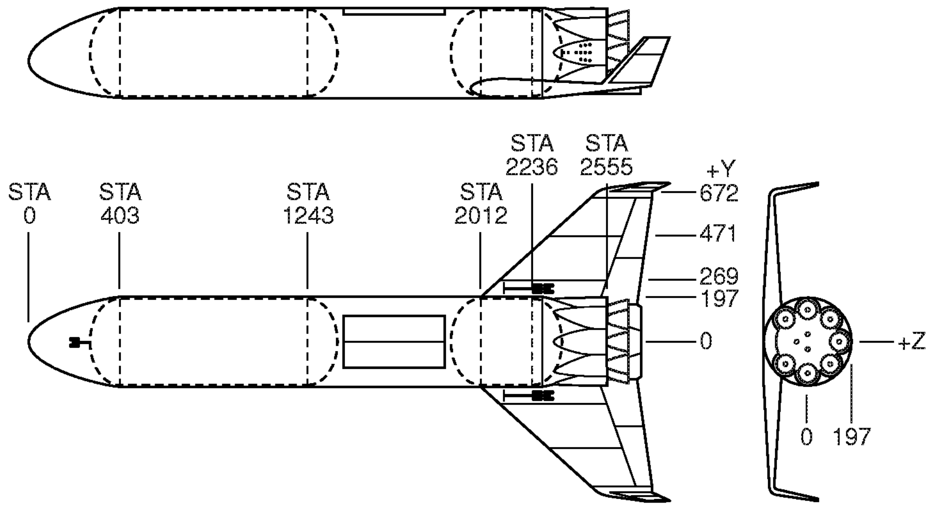

Figure 1.0. WB-003 reference configuration.

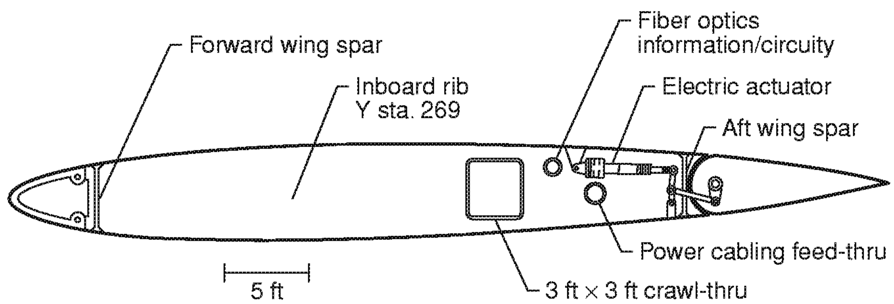

Figure 1.1. Rib cross section at wing station Y 269.

Access to the wing interior is available via the wing's root rib in the plane of the rib at x = 2420, y = 197 just behind the main gear well. The main gear is stowed between x-stations 2114 and 2375 and in between the wing root rib and the inboard intermediate rib. The main gear trunion is located at the 2114 station, and the gear is swung rearward for stowage. The rear panel of the main gear wheel well is removable to provide a second access to the wing volume. A 3 × 3 ft cutout is provided in the inboard rib as a crawl-through (Fig. 1.1). The crawl-through space in the outboard rib (not shown) is estimated as 2.5 × 2.5 ft when allowing for structure and thermal protection. Separate fiber optics and power cabling pull-throughs are provided at 60- and 65-percent chords respectively (Fig. 1.1).

The actuators for the tip fin controllers are located in the plane of the wing's interior cavity. Mechanical power is transmitted to the tip fin controllers via a right angle drive. A 30 × 30 in. removable panel is provided at y 605 on the top surface of the wing for maintenance of the tip fin actuators. Maximum chord thickness at the tip fin locations is 32 inches. After subtracting for structure and thermal protection, the corresponding interior cavity is estimated to be about 24 inches in height. The bottom surface of the wing and tip fin are approximately 11 ft from ground level when the vehicle is resting on its gear.

Advanced Carbon Composites (ACC) components are joined using fasteners and technologies described in Reference 1.6. The mechanical components are protected with high temperature internal insulation. Bearings are of the plain type (as opposed to ball or roller) and are fabricated using special plasma spray coating techniques. Bearings are manufactured using hot isostatic pressing (HIPing). The bearings are operable up to temperatures of 1650°F (Ref. 1.7). The above technologies, and installation techniques for bearings and fasteners, also apply to the molded ACC components used for the body flap and tip fins.

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2.0 Tail Group

Shuttle Background

The Shuttle tail is fabricated from aluminum. The main torque box consists of integrally machined skins and stringers. The rudder is made up of conventional ribs and spars with aluminum honeycomb sandwich surface panels. The rudder is split into two components in the plane of its surface and is equipped with differential gearing so that the rudder can be used both for directional control and for aerodynamic braking.

WB-003 Concepts

The tip fin controllers, as configured, provide both directional control and energy management. The two fixed fins, left and right, are 20 ft high × 13 ft base × 5 ft tip. The chords are 2 ft thick at the root, tapering to 0.6 ft at the tip. The two outboard movable panels (L & R) are 17 ft high × 9 ft base × 6 ft tip (Fig. 2.0).

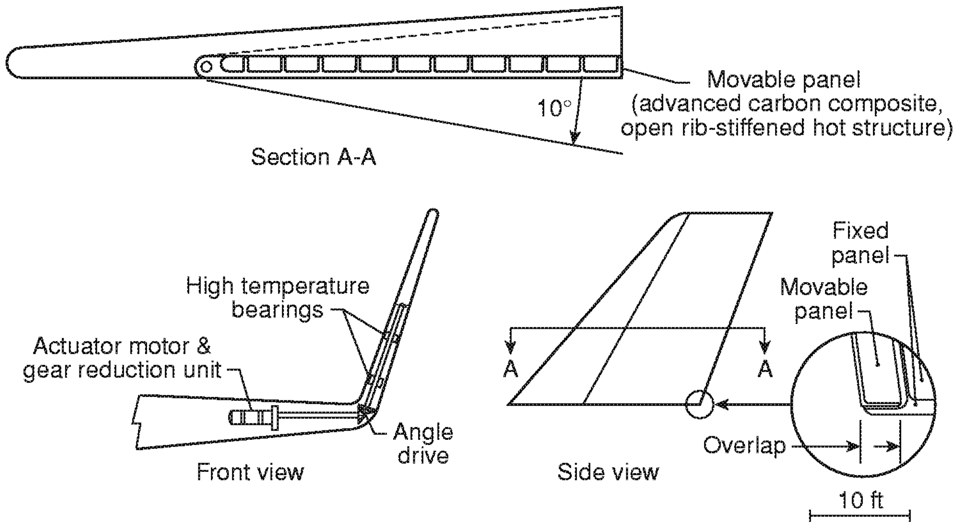

Figure 2.0. Tip fin controllers.

The conceptualized structure for the tip fins is as follows:

The components are all fabricated from Advanced Carbon Composite (ACC). The movable surfaces both are used for directional control (when deployed asymmetrically) and as speed brakes (when deployed symmetrically).

The ACC is integrally blade stiffened, with no face sheets on the inside of hinged speedbrake-rudder panels or that portion of fixed fin that supports the movable panels (Fig. 2.0). Thickness of molded ACC composite is based on weight allowance of 2,602 lb for the two fins each having a profile area of 362 ft^2. The corresponding (allowable) thicknesses are 0.20 in. for the outer face sheet and 0.15 in. for the stiffener ribs.

3.0 Body Group

Shuttle Background

The body structure on the shuttle is principally fabricated of skin/stringer aluminum. Exceptions include the payload bay doors which are fabricated from graphite/epoxy in a honeycomb sandwich configuration. Another exception is the aft fuselage where titanium/boron epoxy is used on the thrust structure. Elevons and body flap covers are fabricated from aluminum honeycomb sandwich.

The mid body is constructed of machined aluminum outer panels mounted on 12 main frame assemblies. Boron aluminum tubes are used as stiffeners in the 12 frames. Two longerons at the tops of the frames serve as payload bay door sills and also serve as structural members to react payload and body static and inertial loads. The two longerons also react main propulsion-system-induced bending loads. These latter loads are the result of compression in the forward external tank support strut from engines pre-canted upwards to be able to thrust (more closely) through the composite center of gravity of the external tank with its propellant and the Shuttle orbiter. High-temperature-capability nickel alloy steel hinges are used on the payload bay doors to accommodate temperatures in excess of 800°F.

The aft body thrust structure provides two major load paths; one from the main propulsion downward to the aft-external-tank fitting and forward to react the orbiter and payload inertial loads. The estimated weight ahead of the orbiter's aft attachment point is about 180,000 lb with a 65,000 lb payload in place. The inertially induced axial stresses on the mid body are estimated to be small compared to the propulsion system induced bending stresses.

The main propulsion hydrogen and LOX tanks are external. The tanks are both aluminum. The LOX tank, located at the forward end of the assembly, is monocoque with no stringers but two large ring frames to which a baffle assembly is attached. The hydrogen tank is of skin stringer construction and has no baffles other than the natural baffling effects afforded by the internal skin-stringers and ring frames. The hydrogen tank on the shuttle has a volumetric capacity of 53,515 ft^3; the LOX tank 19,600 ft^3.

WB-003 Concepts

The body group material selections are identified in Figure 3.0. Graphitic composites are extensively used throughout the structure (Ref. 3.1). The structure is divided into four major groups as follows:

Hydrogen tank
LOX tank
Basic structure
Secondary structure

In the CONSIZ mass properties report (Appendix B), 'basic' and 'secondary' structure are listed under one heading. In the following discussions, the nose, intertank, engine fairings, and thrust structure are given the same rank as the LOX and LH tanks. Payload bay doors and payload container, base closeout, and body flap are listed under secondary structure. In regard to the OMS/RCS pod structure, there is no separate listing since these functions are integrated with the thrust-cone and engine fairing structures.

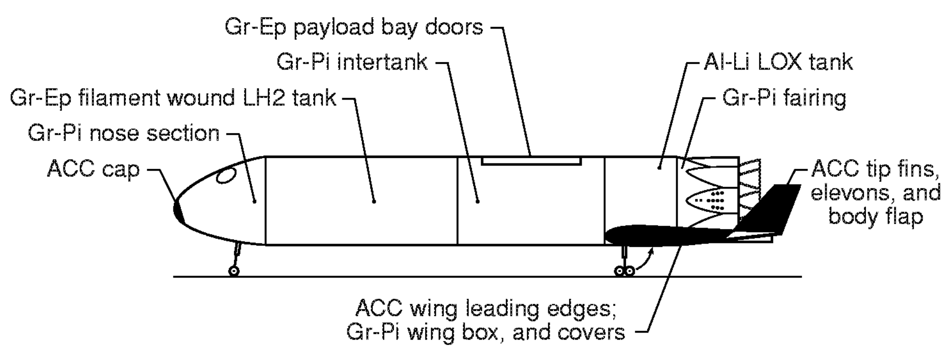

Figure 3.0. Body group materials selection.

For the WB-003 vehicle, the main propellant tanks are integral and therefore must carry inertially induced body loads in addition to sustained internal pressure loads. In tank regions, this means that it would be improbable that either main tank would be subjected to any compressive stresses as long as internal ullage pressure is maintained— even for the worst case scenario for aerodynamic or inertially induced loads. The mid body serves both as intertank adaptor and payload bay. For this arrangement, the structure must react axially induced inertial and aerodynamic loads in tension and compression — compression being possible inasmuch as the intertank/payload bay space is not pressurized. In addition, the structure must accommodate the thermally induced strains resulting from cryogenic tankage attached to a warm structure — i.e. the intertank and aft body. Also, with the LH forward, the intertank must react to an inertial load of approximately 320,000 lb of tank and propellant, plus another 20,000 lb from the nose section structure, nose gear installation, avionics, and power systems. The cut-out in the intertank structure takes up approximately 16 percent of the vehicle's perimeter. When externally induced compressive bending loads from the Shuttle drop tank are considered, it is estimated that the maximum perimeter loads on the intertank of the WB-003 vehicle are still about one-fifth those for the Shuttle; even with the added inertial load of a forward located LH tank. This is partly due to the much greater section modulus (greater depth) of the payload bay section compared to the Shuttle.

Hydrogen Tank

The required hydrogen tank volume is 68,700 ft^3. The tank provides containment for the hydrogen fuel and a path for body loads including axial inertial and slap down. A high temperature thermal blanket (externally applied) is relied upon for a portion of the insulation properties needed for the hydrogen fuel.

The tank is fabricated from Gr-Ep composite honeycomb sandwich. Tank wall thickness is essentially constant between ring frames (actually is reduced gradually for dome and ogive sections). Ring frames consist of 6 in. wide by 4 in. deep bands at 96 in. intervals. These bands amount to 'bumps' on the interior of the tank created by thickening the honeycomb core in this region (Fig. 3.1). The tank is fabricated by first winding the inner face sheet on a mandrel followed by hand lay-up of the core and final winding of the outer face sheet. A filler in the honeycomb core is tailored to meet localized concentrated loads. The sandwich core is cardboard-reinforced polyamide honeycomb (commercial designation: Nomex). The final wall configuration is made up of 7-0.006 in. plies of Gr-Ep in each face sheet. The average core thickness is 2.4 in. and the core density is 4.0 lb/ft^3. The honeycomb core is filled with 3.1 lb/ft^3 closed-cell-rigid-imide foam to a depth of 1 in. (Ref. 3.2) (commercial designation; ROHACELL). The outer 1.4 in. of the honeycomb core is perforated and the entire volume is purged using dry nitrogen at a minimum temperature of -260°F. All weights shown in tables are average values.

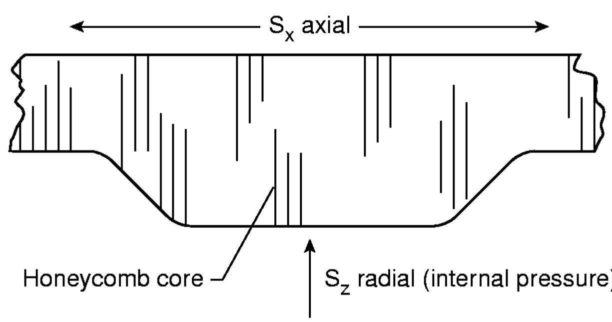

Figure 3.1. Hydrogen tank ring frame concept.

The tank is filament wound on a collapsible mandrel. Eight-ft diameter openings are provided on each end of the tank to allow for the penetration of the tank with an inspection and repair platform. From a practical standpoint, a reasonably large opening is needed in order to minimize the number of components needed for a collapsible mandrel. Both headstock and tailstock in the winder are sized with the eight foot openings. The headstock provides support and the horsepower to drive the mandrel and overcome the mechanical friction and the torque caused by the filaments being applied under tension. The tailstock is the idler, providing support for the mandrel without torque. The headstock's nominal diameter matches that for the base of the aft end of the LH tank, both ends of the intertank adapter and the LOX tank, and the forward ends of the thrust cone and engine fairing. The winding machine could also be used for automated inspection of components prior to assembly. (Refer to Section 70, p. 47.)

The weight breakdown of the LH tank is shown in Table 2.

Table 2. LH Tank Weights

Item	Wt, lb
Tank weight without non-opt	16,971
Non opts (N.O.F. = 1.1)	1,697
Allowance for foam insulation in the honeycomb core	2,806
Total tank weight	21,474

LOX Tank

The LOX tank has a volumetric capacity of 29,372 ft^3. It is fabricated from aluminum lithium (Al-Li 2195). The tank is internally stiffened with stringers and ringframes. The conceptualized Al-Li tank is equipped with two major frames and four minor frames. The two major frames are located at the forward and aft cylinder-to-dome intersections. The four minor frames are spaced at approximately 45-in. intervals in the barrel section between the two major frames. The tank is equipped with skirts of the same Al-Li tank material. Tank wall thickness increases roughly linearly with height from about 0.15 in at the top of the tank to 0.30 at the bottom. The skirts extend for a distance of approximately 4 ft from the dome-to-barrel junctures at the forward and aft ends of the tank. This allows for differential expansion between the aluminum and graphite composites and for working space at the interior portion of the skirt where two structural elements are joined. The two sections are joined using mechanical fasteners. Cryogenic insulation is applied externally to the tank behind the wing-to-body fairings and completely over both forward and aft tank domes. Cryogenic insulation, at a density of 3.1 lb/ft^3, is used at an average thickness of 1.2 in. No cryogenic insulation is applied over the three quarters of the exposed tank barrel section, the thermal blanket serving a dual purpose in this region.

The weight breakdown of the LOX tank is shown in Table 3.

Table 3. LOX Tank Weights

Item	Wt, lb
Tank primary wall weight	12,175
Non opts (N.O.F. = 1.1)	1,218
Insulation weight	1,119
Total	14,512

Basic Structure

The basic body structure consists of the nose section, the intertank, and the aft body thrust cone with fairings.

Nose Section

The nose section is made up of an ACC nose cap and a composite honeycomb ogive frustrum as follows:

An ACC nose cap: 3 ft high × 5 ft at its base
A frustum of an ogive: 30 ft high × 32 ft dia. @ base

The conceptualized structure is as follows:

The nose cap is molded from an ACC composite. The ogive frustum is filament wound of Gr-Pi composite in a honeycomb sandwich. The inner shell is filament wound on a mandrel followed by hand lay-up of 0.8-in. thick honeycomb; then the structure is overwound with another layer of Gr-Pi. Honeycomb core density assumed is 4.0 lb/ft^2. The honeycomb core is a fiberglass reinforced polyimide (commercial designation: HEXCEL). Four 0.006 in. plies are used for both the inner and outer windings. The nose section weight breakdown is shown in Table 4.

Table 4. Nose Section Weights

Item	Wt, lb
Nose section	2,246
Non opts (N.O.F. = 1.1)	225
Nose cap	175
Total nose weight	2,646

Intertank

The intertank serves as the structural load path between the LOX and LH main tanks. The intertank also serves as the payload bay compartment. The intertank is filament wound of Gr-Pi in a honeycomb sandwich configuration similar to that used for the nose section. The openings in the structure for payload bay doors, etc. are made by cutting the filament-wound sandwich shell and then reinforcing the openings with hand layups. The payload bay doors and payload support weights are not included in the intertank structure. They are listed under 'Secondary Structure.'

The conceptualized intertank structure is shown in Table 5.

Table 5. Intertank Weights

Item	Wt, lb
Filament wound honeycomb sandwich (7 plies each side of 0.006 Gr-Pi, 4.0 lb/ft^3 core, intertank area w/o doors = 4,740ft^2	6,623
Non-opts (N.O.F. = 1.2)	1,325
Intertank weight without doors	7,948

Engine Fairing

The engine fairing is fabricated of Gr-Pi in a honeycomb sandwich. The fairing is protected by thermal blanket in selected areas. The fairing is installed in seven segments and is attached to the thrust cone using 5/8-in. self-locking nuts applied to 22 studs that are pre-installed in the thrust cone compression members. For fairing segment removal, the self-locking nuts must be expended and new ones used. Service temperature of the self-locking nuts is well above the temperatures expected in the fairing.

The conceptualized engine fairing structure weights are shown in Table 6.

Table 6. Engine Fairing Weights

Item	Wt, lb
Filament wound HC (5 plies each side 0.006 Gr-Pi 1 in. thick, 4.0 lb/ft^3 core	1,638
Non opts (N.O.F. = 1.2)	328
Total engine fairing weight	1,966

Thrust Structure Cone

The thrust cone is made up of 16, 12-in. diameter compression struts overwrapped with 28 plies of 0.006 in. thick Gr-Pi. It is an open structure that is stabilized by the engine fairing segments that are mechanically fastened along the compression struts installed on the slant height of the cone. The cone is equipped with two diametrically opposite mounting plates for the two aft reaction control system modules. These mounting plates (for the aft primary and vernier thrusters) are an integral part of the thrust cone. In addition, removable trusses are inserted into the aft plane of the cone for the installation of three 4000 lbT OMS engines (Fig. 3.2).

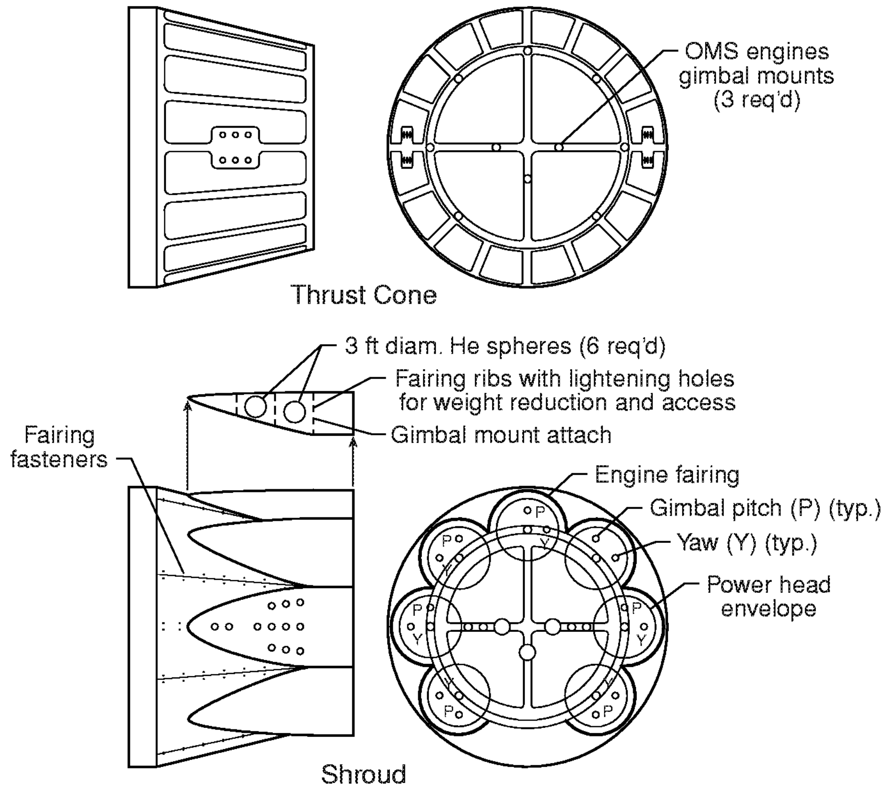

Figure 3.2. Engine fairing and thrust structure.

The conceptualized thrust cone weights are shown in Table 7.

Table 7. Thrust Cone Weights

Item	Wt, lb
16 struts (18 ft long)	2,676
Upper cap	552
Lower cap and LOX tank attachment skirt	777
Non opts (N.O.F. = 1.2)	3649
Total thrust cone weight	7,654

Secondary Structure

Like the Shuttle, the payload bay doors are fabricated from the Gr-Ep honeycomb sandwich. The payload bay closure consists of two doors 35 ft long. Each door is equipped with seven composite hinges and one expansion joint; the latter located at the mid-point of each door. The graphite-epoxy honeycomb sandwich is reinforced with solid graphite/epoxy frames. The honeycomb core of the sandwich is fabricated of polyamide-cardboard (commercial designation: NOMEX). Other hardware includes shear pins and clips. The doors are designed to resist principally torsionally induced shear loads caused by twisting of the body about its principal axis and afford very little resistance to axial compressive loads. End-to-end differential torsional displacements should be relatively small because of the relatively large diameter of the WB-003 vehicle (approximately 30 ft in diameter compared to a width dimension for the shuttle of approximately 20 ft). Aluminum mesh wire is bonded to the outside of the doors for lighting strike protection.

Latching and door rotation mechanisms cause the hardware weight to be disproportionally large compared to basic structure, hence the relatively large non-opt factor for the Shuttle (Appendix D, Table I). In order to reduce these hardware weights, a molded composite of polyeteretherketone (PEEK) reinforced with glass would be used to mechanically lock doors to surrounding structure. Composite molded parts would also be used in the payload bay winch drive mechanisms. Temperatures in the payload bay door region are expected to be less than 600°F (Ref. 3.3).

Table 8. Secondary Structure Weights

Item		Wt, lb
Payload bay door		2,625
Honeycomb sandwich doors 5 plies each side, 1.5 in. thick, 4.0 lb/ft^3 polyamide honeycomb core plus closeouts and beams	1,411	
Non opts (N.O.F. = 1.9)	1,214	
Payload bay support structure and container (Gr-Ep)		3,595
Base closeout, integrally stiffened (area = 706 ft^2)		533
Body flap, ACC internally rib stiffened with no TPS		2,890
OMS/RCS installations		816
Total		10, 459

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3.2 Taylor, A. H. et al,: "Reusable Cryogenic Foam Insulation for Advanced Aerospace Vehicles," Paper No. AIAA-91-0542, A presentation at the 29th Aerospace Sciences Meeting, Reno, Nevada, Jan. 7-10, 1991.

3.3 Wells, W. L.; MacConochie, Ian O.; et al: "Heating Rate Distributions on a Circular Body Earth-to-Orbit Transport Vehicle." Paper No. AIAA-85-0974. A paper presented at the AIAA 20th Thermophysics Conference, Williamsburg, VA, June 1985.

4.0 Induced Environmental Protection

Shuttle Background

The Shuttle thermal protection consists of reusable-carbon-carbon composites (RCC), a high temperature reusable insulation (HRSI), a low temperature reusable insulation (LRSI), and a flexible reusable surface insulation (FRSI) (Ref. 4.1). The Shuttle project has gradually increased the use of FRSI and eliminated the LRSI. The RCC components are all molded. The HRSI are all rigid sintered silica tile. The FRSI is a high temperature NOMEX felt blanket material usable up to about 700°F.

The distribution of the various types of external insulation by weight percentages for the Shuttle shows HRSI as having the highest weight percentage (Table 9).

Table 9. Shuttle TPS Distribution

Type of Insulation	Weight Percentages
RCC	16
HRSI	57
LRSI	13
FRSI	5
AFRSI	9
Total	100

The above data were derived from Shuttle codings for external insulations. Included in this category, however, are the insulations utilized behind the RCC wing leading edge pieces (1,200 lb). This insulation is used to protect the wing's front spar. Insulation is also used on the bulkhead behind the RCC nose cap (247 lb). An estimated 35 percent of the total Induced Environmental Protection Category weight is devoted to miscellaneous such as gap filler, rub seals, bonding agents, closeouts, and carrier panels. This does not include the bulk insulations.

Tiles and blankets are attached to the Shuttle structure with an RTV 560 bonding agent. A Nomex strain isolation pad (SIP) is used beneath the tiles to accommodate the thermal mismatch between the tile and the aluminum structure. Blankets and tiles are typically expended when removed.

Reinforced carbon composites (RCC) are mechanically attached to the nose cap, tail, and wing leading edges. The RCC wing leading edges (or "C" sections) are removed for repair or replacement via plug inserts in ceramic tiles that give access to fasteners that attach the carrier panels to the wing structure. The carrier panels above and below the wing (when removed) provide access to eight A286 bolts that attach the "C" sections to Inconel 718 brackets.

Purge, vent, and drain (PVD) are included under this code for the Shuttle. A brief description of the systems is as follows.

Purge

The Shuttle has three main purge circuits. Circuit No. 1 is for OMS, the wing and tail cavities, the lower forward fuselage, the forward RCS, and the startracker. Circuit No. 2 is for the mid-fuselage equipment bay, the payload bay, and payload bay doors. Circuit No. 3 is for the main engines, its internals, and the volume in the vicinity of the engines. The purge medium is conditioned air.

Vents

The Shuttle nose section, payload bay, and engine compartments are vented to ambient pressure. To this end, the payload bay is equipped with a total of four 10 in. × 24 in. doors and six 12 in. × 18 in. doors. The engine compartment likewise is equipped with vents; two 9 in. × 9 in. and two 12 in. × 16 in. doors. The nose section has four small vent doors. All doors are electrically actuated.

Bulk insulation and heaters are used to further control (or modulate) temperatures within the Shuttle. A 1995 Rockwell mass properties report shows the following weight assignments for bulk insulation (Table 10).

Table 10. Internal Insulation

Location	Wt, lb
Forward RCS module	165
Forward body	105
Crew module	432
Body P/L bay doors	347
Mid-body	1508
Aft-body OMS/RCS	450
Hydraulic lines and actuators	145
Total	3152

In addition to the above, active thermal control is used in the form of electrical heaters. In the forward RCS module area, 29 lb is assigned to heaters; and in the vicinity of the crew module, 6 lb.

WB-003 Concepts

The thermal protection system for the WB-003 vehicle includes area blankets, leading edge pieces, and internal flexible insulation. No tiles are used. The elevons and tip fins are carbon-carbon-composite hot structure. The body flap is also a hot structure.

High temperature blanket insulation is used over an estimated area of 24,226 ft^2. This includes the top and bottom surfaces of the wing and body. Tailorable Advanced Blanket Insulation (TABI) is used for windward body and wing surfaces, and Advanced Flexible Reusable Surface Insulation (AFRSI) is used for leeward surfaces (Fig. 4.0). The AFRSI is a quilted blanket that is more durable than the FRSI and is usable up to approximately 1200°F. Corrugations in TABI shown in Figure 4.0 represent a rigid composite polyimide material that is imbedded in the blanket material to improve compression, shear stiffness, and strength (Ref. 4.2). ACC is used for the nose cap and wing leading edges. An estimated, 25 left hand

and 25 right hand molded ACC wing leading edge pieces will be needed for the wings. The heaviest molded leading edge piece weighs an estimated 75lb. The installation and removal techniques for the WB-003 vehicle would be similar to those used on the Shuttle.

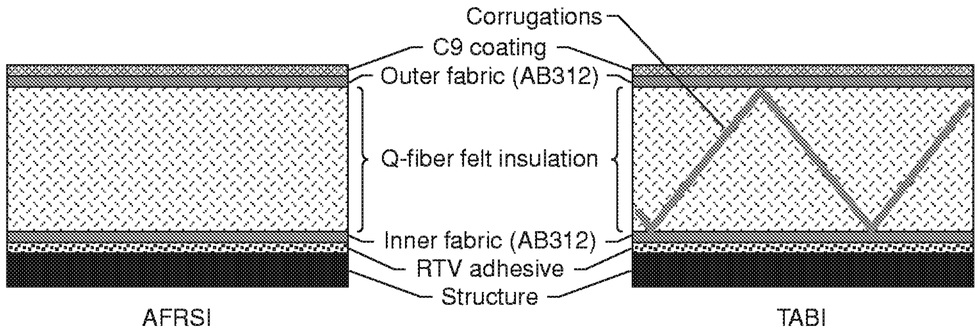

Figure 4.0. Depiction of the AFRSI and TABI thermal protection systems.

The average unit weight (based on surface areas) of ACC wing leading edge pieces = 6 lb/ft^2. The two foot-wide pieces vary in chord height at the forward spar attach point from 2 ft in height to 1 ft at the tip; and the chordwise direction from approximately 2 ft at the wing root to 1.5 ft at the tip.

The idea of utilizing thermal blanket so extensively on the WB-003 vehicles is considered conceptual, pushing the art, but plausible. TABI is an integrally woven stitched quilt of a silica, NEXTEL, silicon carbide fabric with an insulative filler of Q-felt-NEXTEL-alumna 9. Maximum heat rate capability is 35 BTU/ft^2-sec. TABI is bonded to the structural surfaces using Room Temperature Vulcanizing (RTV) adhesive (Ref. 4.2 and 4.3). TABI is used on the windward surfaces of the vehicle at an estimated average weight of 1.2 lb/ft^2.

AFRSI is used on the vehicle's leeward surfaces at an estimated average unit weight of 0.4 lb/ft^2. Like the TABI, the AFRSI is a woven blanket material that is attached to the vehicle using RTV. Both types of blankets are coated to rigidize them. The coating, however, renders the blankets brittle and susceptible to damage from impact. Both blanket concepts are made in 30 in. squares.

Internal insulation, where needed, is estimated at 1,000 lb. Overall, lessons learned from the Shuttle program afford the opportunity for reductions in TPS weights (Ref. 4.4).

The WB-003 vehicle has three purge circuits. The forebody circuit supplies He purge and pressurization gas to the forward RCS module, the avionics, and the power systems. The second circuit services the mid-fuselage OMS and payload compartments. A third circuit services the engine compartment and wing cavities. Purge gas is available from the propellant pressurization systems in the nose, mid-fuselage, and engine compartment. The WB-003 vehicle is equipped with eight 10 in. × 24 in. vent doors. Four are located in the nose section and four are located in the mid-fuselage section. The engine compartment is equipped with two 12 in. × 16 in. doors.

Five of the seven engine fairing pods are used for installation of 3-ft diam. helium spheres. One 3-ft diam. sphere is placed in each of four pods while two spheres are placed in the top-centerline pod (Fig. 3.2).

The above inventory only provides six spheres for the pressurization of seven engines. The mismatch is accommodated by networking; i.e., a system of interconnnecting lines to provide helium flow from selected spheres with redundant valving that provides overall system redundancy and greater flexibility in budgeting. The same concept is applied to storage in the mid-fuselage and nose sections where the same gas is multipurpose being used for pressurization, purge, the operation of pneumatic valves, and for other actuation functions.

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4.4 Arrington, J.P.; and Jones, J.J.: "Shuttle Performance: Lessons Learned" NASA Conference Paper CP 2283 Part 2; and as part of document: Paper by Greenwood et al "Calculation of Shuttle Base Heating Environments and Comparison with Flight Data," p. 653; and paper by Neuenschwander, W.E. et al Shuttle TPS Thermal Performance and Analysis," p.1025. Conference held at Langley Research Center, March 8-10, 1983.

5.0 Undercarriage

Shuttle Background

The Shuttle is equipped with two 44.5 in. dia. × 16.0 in. wide tires for each of the two main gear struts and two 32 in. dia. × 8.0 in. wide tires for the nose gear. The tires are inflated to 350 psi with nitrogen. Based on a design allowable weight of 220,000 lb at landing and a gear weight of 6,718 lb, the current Shuttle has a 3% gear. Nominal load limit per main gear tire is 55,000 lb.

The Shuttle strut assembly is 'pneudraulic' containing both gaseous nitrogen and hydraulic fluid. A floating diaphragm separates the gas from the liquid. The hydraulic fluid is formulated especially for use in zero gravity. Hydraulic pressure is used for steering and for deploying both the nose and main gears. The hydraulic fluid for the nose gear is supplied via a line from the APUs located in the aft body section.

The arresting system consists of disc brakes installed in the main rolling gear. Carbon-lined beryllium rotors are splined to the inside of the wheel. Carbon-lined beryllium stators are splined to the outside of the axle assembly. The brake assemblies located in the main gear weigh 782 lb and account for 34 percent of the main rolling gear weight. Like the nose gear steering, the main gear brakes are powered by hydraulic fluid under pressure from the three APUs. A 40-ft diam. drogue is deployed during rollout to reduce the loads on the nose gear and to reduce the amount of energy that the brakes would otherwise have to absorb.

WB-003 Concepts

Each main gear strut on the WB-003 vehicle is equipped with four tires instead of two. Two tires are used for the nose gear. All ten tires are 34.5 in. diam. 9.75 in. wide with 26 ply and a load carrying capability of 30,000 lb each. The rated upper speed limit for the tires is 225 knots. Each tire weighs 120 lb.

Table 11. Landing Gear

Item	Wt, lb
Nose rolling gear	237
Structure	934
Controls	200
Main rolling gear	2,845
Structure	3,177
Total undercarriage and auxiliary systems	7,393

The WB-003 percent gear, based on an abort landed weight of 291,877 lb, is at 2.5 percent. The percent gear, based on design allowable landed weight of 264,512, is 2.8%. The main gear is equipped with electrically actuated graphitic disc brakes. The main structure is also composite. The shock strut is pneumatic instead of hydraulic and is equipped with a coulomb damping system (Figs. 5.0 and 5.1). The coulomb damping pads are fabricated of beryllium and are lined with carbon. The coulomb damping cylinder is also fabricated of beryllium and is lined with carbon.. There should be no friction pad replacement required for 500 landings — only inspection. The tires are pressurized with helium to 350 psi. The gear must be capable of withstanding a return-to-launch-site (RTLS) landed weight of 297,000 lb. The two main gear shock struts are pressurized to 350 psi (also with helium). For the static case, each strut is required to support approximately 150,000 lb. The composite shock strut is considerably larger than the equivalent capability metallic-hydraulic strut. The outside diameter of the pneumatic-composite strut is 24 inches. Helium is used to preserve the commonality in the system with the helium used for purge and pressurization throughout the vehicle.

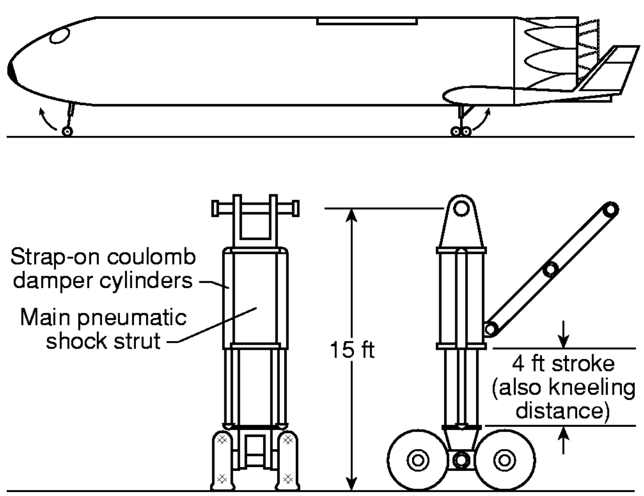


Figure 5.0. Composite-pneumatic strut with kneeling capability.

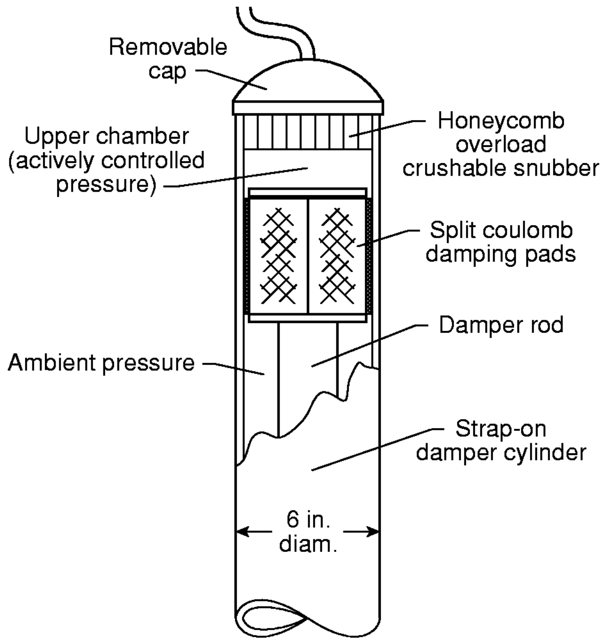


Figure 5.1. Coulomb damper.

The dampers are actively controlled using the main gear helium source. The helium gas is injected into the upper chamber of the coulomb damper. As pressure is increased above ambient, two semi-cylinders of beryllium material (lined with graphite) are forced against the inner walls of the strap-on coulomb struts. The damper pads are confined to the end portion of the damper rod between two flanges. Unless the flow of helium is sustained, the pressure in the center of the spool and behind the pads bleeds down. The function of the dampers is to dampen the vertical motion of the gear during the landing impact and roll-out phases.

Automated precision landings are made with sink rates limited to 4 ft/sec at touchdown. Strut overloads are accommodated by expendable crushable honeycomb cartridges installed on each side-mounted coulomb damping cylinder. These cartridges can be replaced simply by removing the top caps on the coulomb cylinders. As an estimate, it is assumed that the sink rate of 4 ft/sec would only be exceeded every 5th flight requiring cartridge replacements.

Kneeling capability is available simply by lowering pressure in the pneumatic struts (Fig. 5.0). This capability would reduce the work height from floor to bottom of the vehicle eliminating the need for scaffolding for many portions of the maintenance activities.

6.0 Main Propulsion

Shuttle Background

The Shuttle has three main engines. Each engine produces 470,000 lb. vacuum thrust at a nominal specific impulse of 455 seconds. The engines employ a staged combustion cycle, propellants being partially burned at high pressure and relatively low temperature in pre-burners, then completely burned at high pressures and temperatures in the main combustion chamber before expansion in the nozzle. The engines can be throttled over a range of 65 percent to 109 percent of the vacuum thrust value. The main combustion process takes place at 3000 psi and 5500°F.

The nozzle exit-plane diameter is 8 ft for an expansion ratio of 77.5. This expansion ratio was partly dictated by necessity to limit the size of the engine bells in order to obtain the desired gimbal angles for steering (Ref. 6.1). Another limitation for engine bell size is, of course, flow instability at sea-level — over-expansion giving unwanted lateral vibration of the nozzle. Weight limitations for the engines necessitated greater use of welded joints (versus fastened) for many components complicating the manufacturing process. The extremely harsh environment in the combustion process necessitated the use of exotic alloys such as those containing silver and zirconium. The nominal weight of on SSME is 7,500 lb. This weight includes the gimbal system and other accessories. If the pressurization and feed system is included (prorated over the three engines), this value becomes about 10,000 lb.

The engines are pre-canted, bell upwards, so that thrust produced will pass through an off-axis center of gravity caused by the presence of the external LOX/LH tank. A crossfeed system is required to transfer main propellants from the external tanks to the orbiter engines. The weight penalty for the mechanism is 1,010 lb. This does not include side load struts or actuators. The attendant operations associated with the crossfeed include leak and functional testing. This operation takes several days. LOX and LH feedline diameters for the shuttle are 17 inches. The LOX line is approximately 90 ft long; the LH line is approximately 12 ft long.

Two 17 in. fill and drain lines are connected at pylons near the engine compartment, each line feeding to the bottom of the respective main LOX and LH tanks. A vent valve is located beneath a fairing on the nose on the external tank for LOX. The main feedlines and disconnects are mounted in a pad-mounted pylon at the engine compartment level. The fill and drain port for LOX is on the righthand side and LH on the left side.

WB-003 Concepts

The rocket engines identified for the WB-003 vehicle are very similar to those used in the current shuttle in that they are LOX/LH fed, having fixed bells (Appendix A). The engine envelope is similar to that shown in Fig. 6.0 for the Shuttle. A new feature (over the old Space Shuttle main engines) would be the use of a Block II engine controller that is equipped with a health monitoring system (Fig. 6.1). Seven engines are required. Each engine is equipped with two-axis gimbal capability requiring a total of 14 actuators (Fig. 6.2). Since the actuators are electrically driven (versus hydraulic), it will be necessary also to have motor controllers for the electric actuators in addition to the engine controllers (Fig. 10.1).

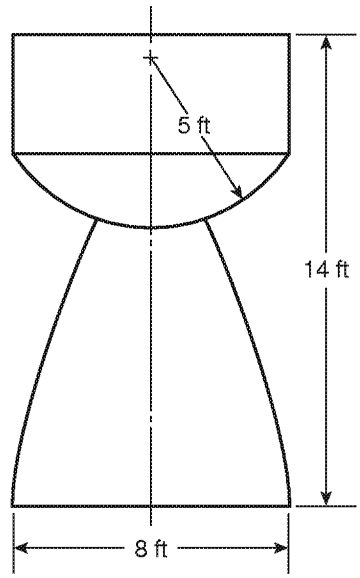
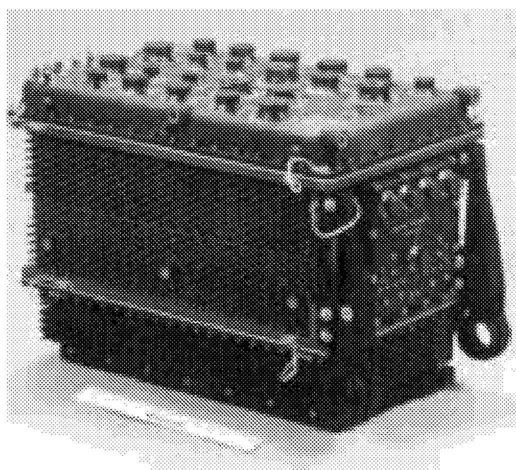


Figure 6.0. Main engine clearance envelope.



Wt = 205 lb
Dimensions: 24 in. w × 14.5 in. × 17.3 in.
Location: installed on engine
(Honeywell)

Figure 6.1. Block II main engine controller.

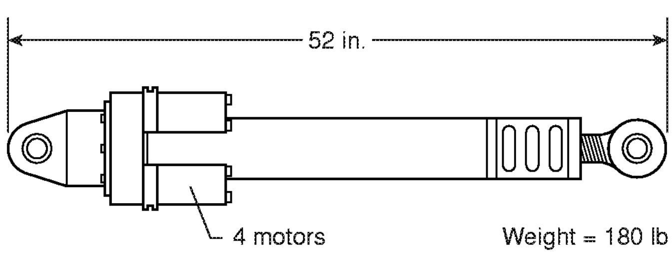


Figure 6.2. Quad-redundant electro-mechanical actuator.

If a motor controller were to fail on a main engine gimbal during ascent, the remaining engines would simply be gimbaled to accommodate the loss of the gimbal authority. In other words the thrust vectoring of the propulsion system would be degraded but might still be rated as fail-safe-fail-operational. The WB-003 vehicle, having seven engines, could be considered inherently fault tolerant providing engine out capability, the remaining six engines reverting to emergency power. Likewise, the loss of one engine gimbal actuator would only yield a one seventh (or 14%) loss of thrust vector capability. The remaining six engines should be easily able to compensate for this loss.

The salient characteristics of the engines are as follows:

7 engines are required. The weight of each engine without accessories = 5805 lb.
Length = 14 ft; bell exit-plane diameter and power head clearance envelope diameters both equal 8 ft. Sea level thrust is 452,000 lb.

7 engine Block II engine controllers are required (Fig. 6.1).
Each engine controller weighs 205 lb and is 24 in. × 14.5 in. × 17.3 in.

14 quad-redundant DC electric actuators are required for 7 engines in order to have full gimbal capability (Fig. 6.2).
Each actuator weighs 180 lb and has an envelope of approximately 10 in. diameter.
Each of the 4 motors delivers 17 hp for a gross hp of 68 and a net of 58 hp
(based on end-to-end efficiency factor of 85 percent).

Two 18 in. dia. lines from the LH tank are used for feed and drain. The two lines attach on either side of the aft dome of the LH tank and are directed down and outward beneath the payload bay and behind the vertical LOX-tank-to-wing fairing, and finally to the main engine LH manifold. A single 26 in. line feeds from the center of the aft LOX tank dome to the engine manifolds (Fig. 6.3). LOX and LH fill and drain ports are located on either side of the main engine compartment.

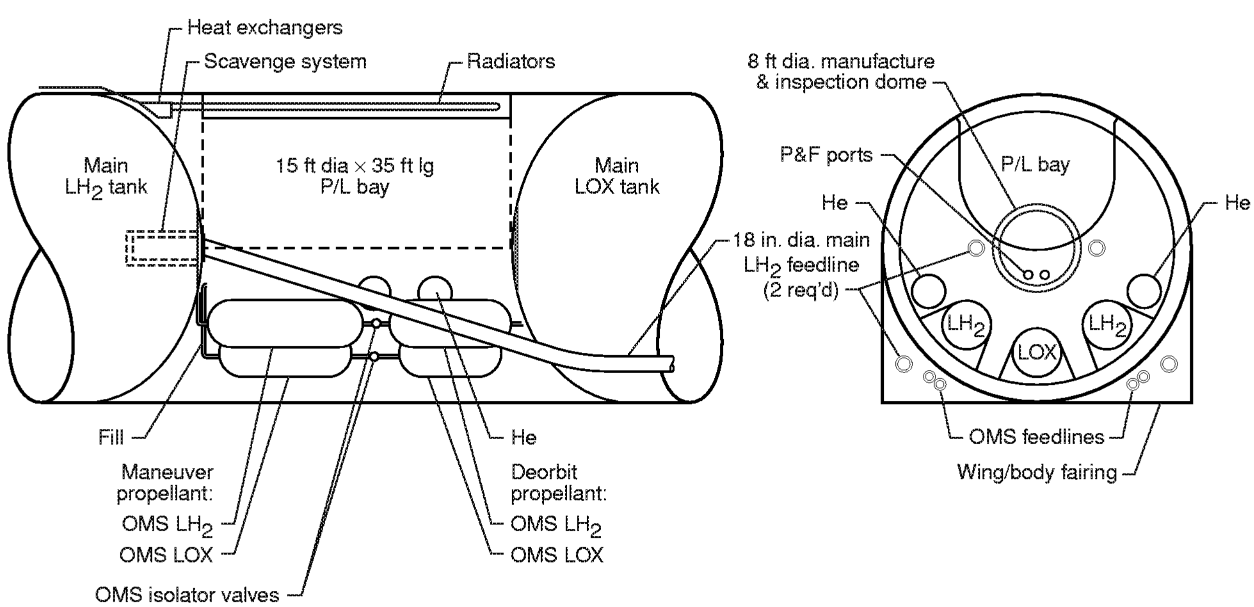


Figure 6.3. Main propellant feed lines and storage.

References

6.1 Dankhoff, W. F.; Herr, P. N.; and McIlwain, M. C.: “Space Shuttle Main Engine (SSME) — the Maturing Process.” *Astronautics and Aeronautics*, Jan. 1983, p. 26.

7.0 Propulsion, Reaction Control (RCS)

Shuttle Background

The impulse density for the Shuttle RCS storable propellants N_2O_4/MMH (nitrogen-tetroxide-monomethyl-hydrazine) is 20,362 lb-sec/ft^3 for a nominal specific impulse of 288 seconds. The Shuttle uses three spherical tanks for fuel, three spherical tanks for oxidizer, and six spherical tanks for helium pressurant. This includes tankage for both forward and aft RCS. The Shuttle has 14 primary thrusters in the forward module and 12 in each of the aft pods. In addition, 2 vernier thrusters are located in the forward module and 2 verniers in each of the aft pods. Nominal thrust of the primaries is 870 lbT; nominal thrust for the verniers is 25 lbT.

WB-003 Concepts

The WB-003 vehicle utilizes an all hydrogen-oxygen system for the RCS (Figs. 7.0-7.3). The impulse density for the WB-003 LOX/LH propellants is 7,274 lb-sec/ft^3 based on a nominal specific impulse of 410 seconds; or the LOX/LH cryogens require about three times the storage volume for the same impulse that storables could provide. However, the lower packaging density of the cryogens is more compatible with the WB-003 class vehicles in that they typically have more ‘casual’ volume. Advantage of the cryogens over the storables include: the lower mass of the fully loaded system, higher performance, and commonality of the propellants with the main propulsion system. A notable difference between the Shuttle storable propellants and the WB-003 cryogens for the RCS is that the latter require ignition systems.

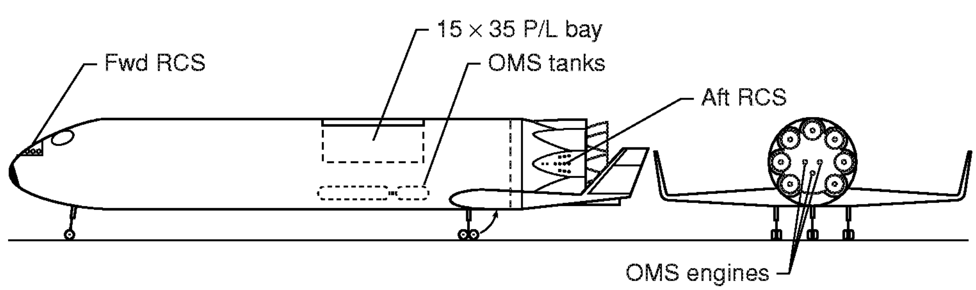


Figure 7.0. RCS/OMS propulsion.

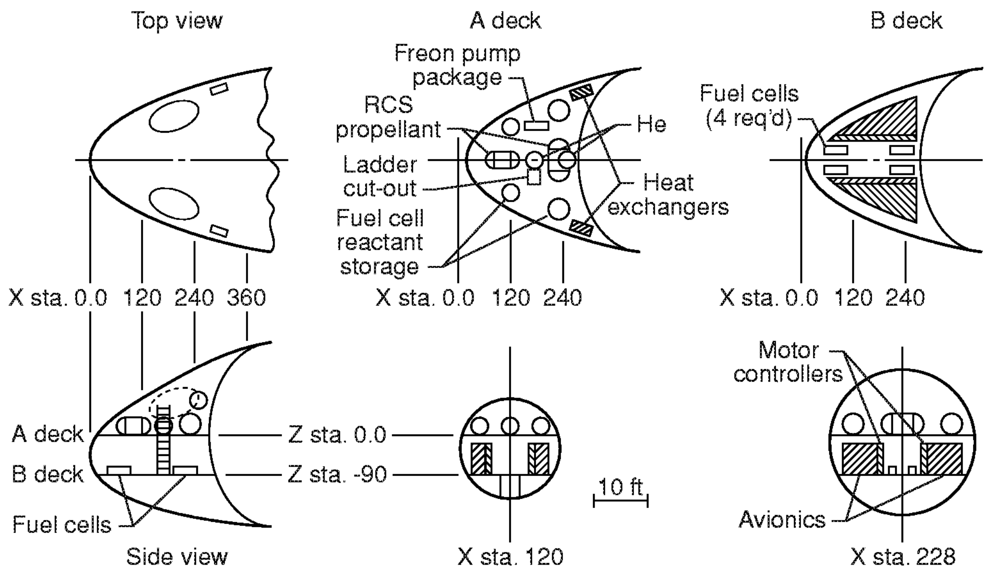


Figure 7.1. Nose section subsystem packaging.

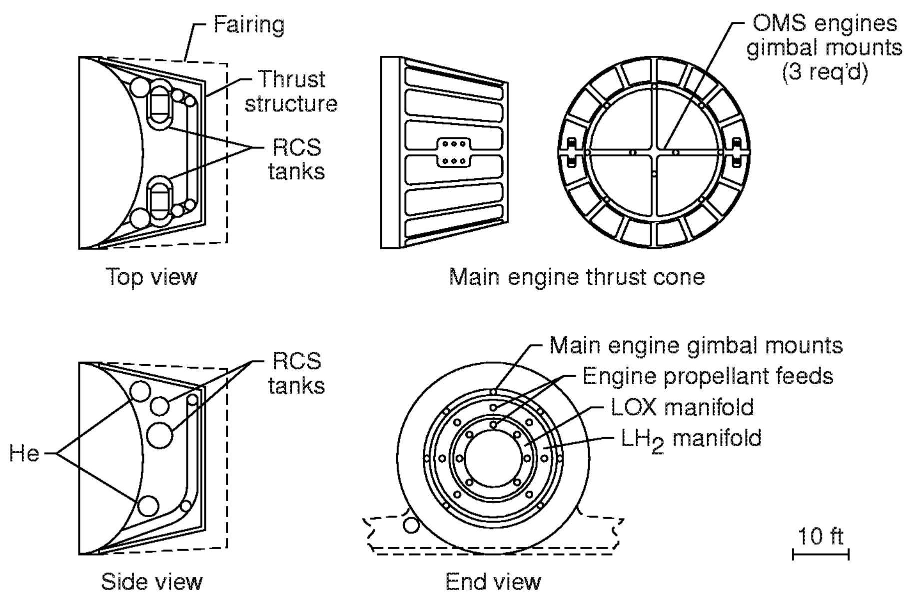


Figure 7.2. Aft body subsystem packaging.

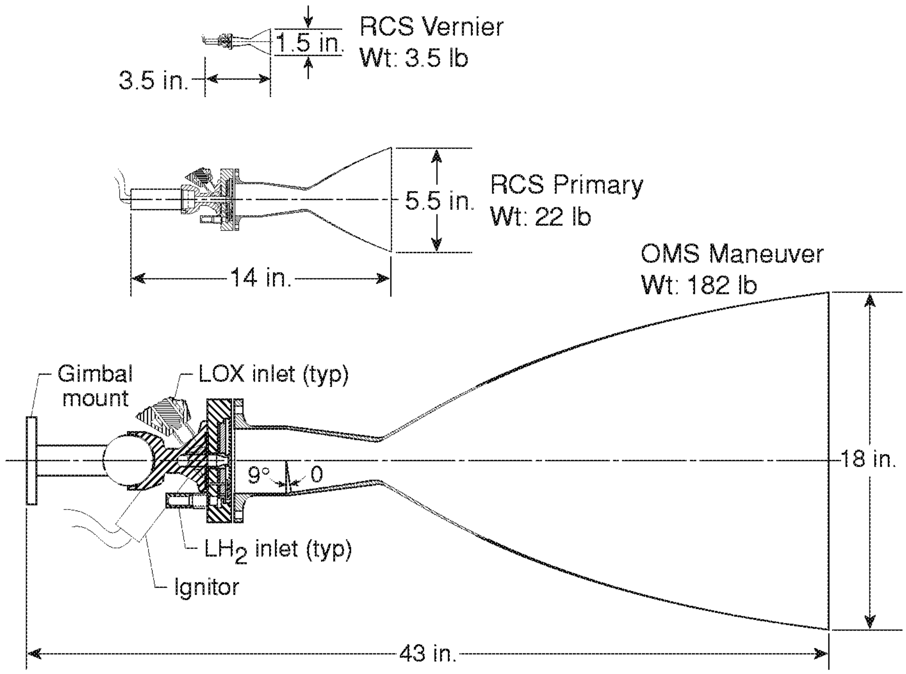


Figure 7.3. Auxiliary propulsion.

A study was made by Rockwell International under direction of Lewis Research Center on an all LOX/LH vehicle. It is entitled "Integrated Hydrogen/Oxygen Technology Applied to Auxiliary Propulsion" or IHOT (Ref. 7.1), Two high pressure helium tanks supply ullage pressure independently of the LH and LOX storage tanks. Downstream of the Helium tanks the pressure is reduced to 195 psi from 4000 psi for use in the RCS system. A second set of regulators reduces the pressure to 25 psi for use in the OMS system (Fig. 8.0). Characteristics of both the RCS and the OMS propulsion system from the IHOT study are given in Table 12. The same expansion and mass ratios used in the IHOT study are used for the WB-003 vehicle. The propellant masses are those identified with the vehicle used as a model for the IHOT study. These weights are approximately 25% lower than those identified for the current vehicle. The propellant masses and volumes in Table 12 are provided as background information.

Table 12. IHOT Auxiliary Propulsion Characteristics

Rocket Engine Performance

	Expansion Ratio	PC, psia	Isp Delivered, sec	Thrust, lb	Mixture Ratio
Primary	22	150	423.8	870	4
Vernier	22	150	419.5	50	4
OMS	100	800	462.2	4000	6

Line Sizes, inches

	Engine (O2)	Engine (H2)	Manifold (O2)	Manifold (H2)
Primary	0.75	1.25	1.5	1.25
Vernier	0.25	0.25	0.5	0.5
OMS	1.5	1.5	1.5	1.5

Propellant And Pressurant Storage*

	O2 Mass, lb	H2 Mass, lb	He Mass, lb	O2 Volume, ft^3	H2 Volume, ft^3	He Volume, ft^3
Primary	1249	312	47.2	23	97.5	(incl., OMS)
Vernier	310	78	(included)	(included)	(included)	(incl., OMS)
OMS	16281	2714	112.3	240	678.4	56.7
Totals	17840	3104	159.5	263	775.9	56.7

*IHOT Study Option 4.

To save weight, some sort of scavenging system may be practical. As one approach for a WB-003 class vehicle, residual propellants from the main propulsion system would be recovered. Weight of residuals recoverable versus the weight, complexity, cost, and operational considerations of the scavenging system would have to be quantified.

RCS propellant storage for the current study is shown in Figures 7.1 and 7.2. The RCS tanks for this study are monocoque. The tank material is AL-Li and the support straps are S-Glass/Epoxy. The tanks are covered with multiple layers of silverized mylar; each layer separated by a Nylon net.

For the WB-003 concept, one set of cylindrical LOX and LH tanks is used for the forward RCS and two sets for the aft RCS (Figs 7.1 and 7.2). A set consists of one LOX tank and one LH tank. The aft RCS tank sets are identical to the forward sets. Double the number of spherical tanks were first tried. Deciding how many tanks to use and their shapes and sizes is a study in itself. Such factors as development, manufacturing and inventory costs, weight, and heat leak rate are some of the parameters that would have to be considered. Because of the commonality of propellants, there may be options wherein end-domes from one propulsion system could be used in the other with commonality in diameter but varying barrel lengths. If spherical end-domes are used, in theory, two end domes could be used to make one spherical tank. Tank dimensions and weights for the WB-003 vehicle's RCS pressurants and propellants are given in Table 13. A cross-feed is provided between the two aft LOX/LH tank sets for the purpose of providing lateral trim and tank redundancy.

Table 13. WB-003 RCS Storage Tankage

Propellant	Tank Wt, lb			Size,	No.	Storage
	Structure	Insulation	Total Each	ft	Req'd	Pressure, psi
LOX	32	5	37	2×4.3	3	195
LH2	124	22	146	3×7.4	3	195

The following is a summary of the RCS engines used (Fig. 7.3):

18 primaries at 870 lb. thrust each, exit dia. = 5.5 in., length = 14 in., wt = 22 lb each.
21 verniers at 50 lb. thrust each, exit dia. = 1.5 in, length = 3.5 in., wt = 3.5 lb each.
Expansion ratio for all RCS jets = 22 with a chamber pressure of 150 psi

The reaction control engines are distributed as follows:

9 primaries in each aft pod for a total of 18
6 verniers in each aft pod for a total of 12
9 verniers in the forward module

References

7.1 Gerhardt, David L.: "Integrated Hydrogen/Oxygen Technology Applied to Auxiliary Propulsion" Contract Report CR-165289 prepared by Rockwell International for Lewis Research Center, Sept. 1990.

7.2 Knoll, Richard H.; and DeWitt, Richard L.: "Thermal Performance of a Modularized Replaceable Multistage Insulation System for a Cryogenic Stage" NASA TN D-8282 Lewis Research Center, Jan. 1977.

8.0 Propulsion, Orbital Maneuvering (OMS)

Shuttle Background

The OMS propellants and engines on the shuttle are located near the tail in two pods that project above the basic structure's outer moldline. The propellants are storable but toxic. The original idea was that the pods could be easily removed for maintenance. Two 6000 lb thrust-hypergolic-propellant engines are used. The two OMS engines are pressure-fed operating at a chamber pressure of 125 psi and a mixture ratio of N_2O_4-to-MMH of 1.65, and delivering a nominal thrust of 6,000 lb at an Isp of 213 sec. The dry weight of each engine is 260 lb. The fuel and oxidizer supply system is operated at 250 psi; the helium pressurant at 4,875 psi. A crossfeed is provided between propellant tanks for the purpose of trimming the vehicle prior to reentry.

WB-003 Concepts

Three 4000 lb thrust LOX/LH engines are used on the WB-003 vehicle (Figs. 7.0, 7.2, and 7.3). Each engine weighs 181.8 lb with gimbal system and is 43 in. long, with an 18-in. diameter bell. The expansion ratio for the engines is 100. The technology for such an engine was demonstrated in 1973 (Ref. 8.1).

Compared to Shuttle, the impulse density of cryogenic propellant is approximately one-half that of the storables. It is estimated that the LH pump will require a 81 HP electric drive and the LOX a 30 HP drive. The pump/motor assemblies are estimated to each weigh 132 and 62 lb respectively. Three pump sets are employed, one set for each of the three OMS engines. Assuming a motor efficiency factor of 0.85, the power demand for three OMS engine/pump sets would be 292 kW. The peak power output from the four fuel cell sets assumed for the vehicle equals 320 kW. A pump efficiency factor of 0.70 was used in the calculation of electric drive horsepower.

Because of the considerable volume required for the cryogenic propellants, it was necessary to store the WB-003 OMS propellants in the intertank region beneath the payload bay (Fig. 6.3). For this arrangement the distance from the storage tanks to the OMS engines is approximately 60 ft. The storage is divided into insertion and de-orbit storage. The insertion storage is dedicated to final ascent, circularization, and rendezvous.

The de-orbit storage is reserved for de-orbit and related reentry maneuvers. The isolation valve between the two tanks allows flow only from the forward tanks to the rear tanks. The tank weights and sizes are shown in Table 14. Tanks are Al-Li (internally stiffened) and are insulated with alternate layers of silverized Mylar and Nylon net spacers. This is the same insulation system that is used for the RCS tankage and described in reference 7.2.

Table 14. WB-003 OMS Storage Tankage

Propellant	Wt, lb			Dimensions, ft	No. Req'd	Tank Pressure, psi
	Structure	Insulation	Total Each			
LOX	81	29	110	4.7 × 13 (I)	1	25
	56	40	96	4.7 × 9 (D)	1	25
LH	105	75	180	4.7 × 17 (I)	2	25
	68	97	165	4.7 × 11 (D)	2	25

Overall Lengths:
(I) Insertion Tankage
(D) Deorbit Tankage

As explained earlier in section 7.0 (RCS), each OMS engine is equipped with 2 electric pumps – one for LOX and one for hydrogen. Accumulators are used on the discharge side of the pump to give a constant engine inlet suction pressure (Fig. 8.0).

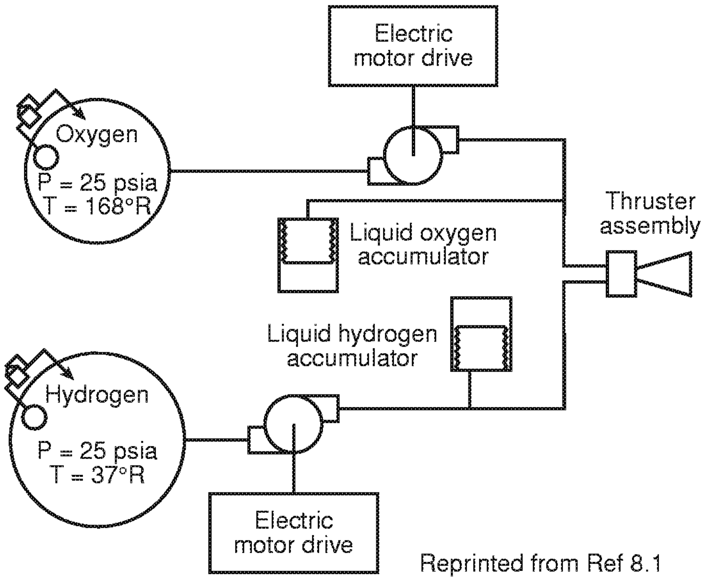


Figure 8.0. Orbital maneuvering propulsion system.

The He pressurization gas for the main propulsion, RCS, and OMS are all stored in spheres (Table 15). Two-ft spheres are used in the nose section for the forward RCS and 3- ft spheres elsewhere.

Table 15. Helium Pressurization and Purge Storage (Capacities and Budgets)

Location	Usage	Tank Size, ft	Tank No.	Capacity, lb	Budget, lb
Nose	RCS verniers & nose gear strut	2	2	20	10
Mid-body	OMS & main gear strut	3	4	140	112
Aft	Aft RCS Primaries, verniers & main rocket engines	3	6	210	168*

*121 lb is budgeted for main engine pressurization; 47 lb for aft RCS for total of 168 lb.
Subsystem miscellaneous volume purge is ill-defined but allowed for in the margins above.

Reference

8.1 Herr, P. N.; and Schoenman, L.: "Demonstration of a Pulsing Liquid Hydrogen/Liquid Oxygen-Thruster;" AIAA paper no. 73-1244, Nov. 1973.

9.0 Prime Power

Shuttle Background

The Shuttle is equipped with 3-28 Volt fuel cell sets (Fig. 9.0). The installed weight of three fuel cell sets is 3,987 lb. Oxygen is taken off the fuel cell oxygen dewars for breathing. Each fuel cell set can deliver power at 12 kW continuously at 28 Volts. Since the average power demand for the Shuttle is 14 to 16 kW and the peak demand is 22 to 24 kW, it can be seen that the Shuttle could be operated without compromising a mission on two fuel cell sets and in a power down mode, on one set. The failure of two of the three sets require an emergency return to Earth. One set of Shuttle fuel cell reactant dewars is shown in Figure 9.1. In the Shuttle mass properties reports, the auxiliary power units (APUs) are listed under this code. Three APUs are required to power the hydraulic system for a total weight of 871 lb. They supply hydraulic power to aerodynamic surfaces, main engine gimbals, and the landing gear.

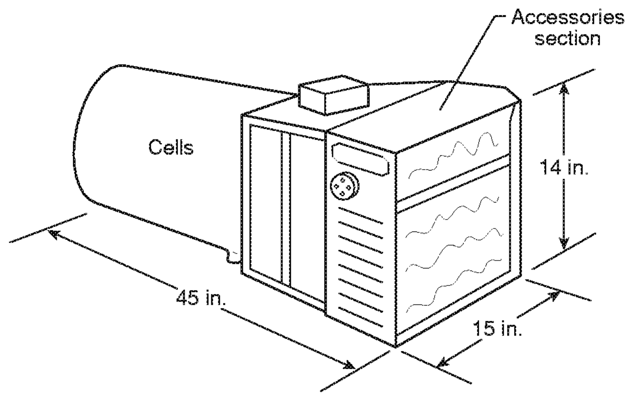


Figure 9.0. Shuttle fuel cell.

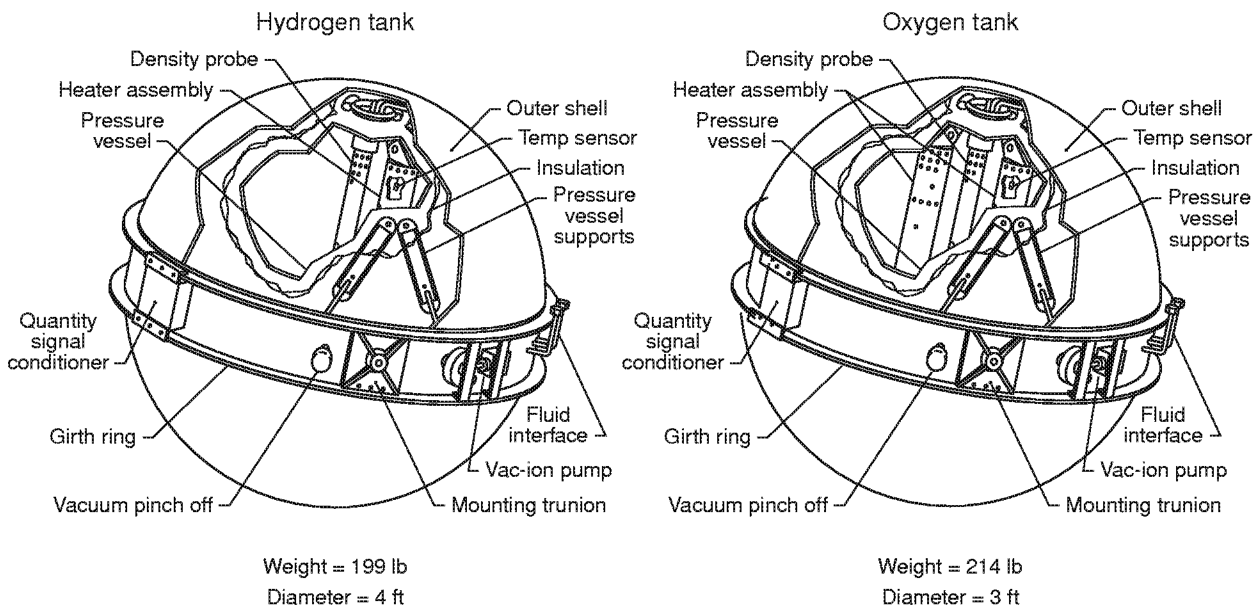


Figure 9.1. Shuttle fuel cell reactant storage (Honeywell).

WB-003 Concepts

Four fuel cell sets are used on the WB-003 vehicle, each capable of delivering 80 kW of power at 270 Volts DC. A 270 Volt supply is necessary for efficient operation of electric actuators. It is estimated that each fuel cell set would be 146 in. long × 15 in. wide × 14 in. high and weigh 340 lb. Solid state converters are used to step the voltage down to 28 Volts for avionics and other subsystems. This fuel cell power source eliminates the need for the APUs used on the current Shuttle.

Two reactant storage sets are used (Table 16). The systems are located in the nose section of the vehicle (Fig. 7.1). The hydrogen dewars are operated at 285 psia and the oxygen dewars at 950 psia. The dewars are similar to those used on the current Shuttle, having double walls with Mylar-Nylon overwraps. The inner shell of the oxygen dewars are fabricated from Inconel 718 and hydrogen dewars from Al 2219 (Fig. 9.1). The outer walls of both tanks are fabricated from 2219 aluminum. The fluid capacity for one Shuttle dewar is 92 lb; for the LOX, 781 lb. The total capacity for two sets is 1,746 lb. The CONSIZ allocation for the mission is 1,612 lb. The LOX can be depleted to about 6%; the LH to about 2%. Two Shuttle reactant dewar sets appear to adequately provide storage for the reactant requirements as envisioned by the CONSIZ program. However, redundancy requirements may make it necessary to add one more set. The two-set system amounts to a fuel cell supply with only dual-tank redundancy. (All valving and other plumbing could be installed at the quad-redundancy level.) The dry weights shown for dewars in Table 16 allow for purge disconnects, vents, filters, insulation, plumbing and other items.

Table 16. WB-003 Fuel Cell System Weights

Item	No. Req'd	Unit Wt, lb	Unit Installation Wt, lb	Total Wt, lb
Fuel cells	4	340	65	1620
Reactant dewar sets	2	604	114	1436
Totals		944	179	3056

10.0 Electrical Power Conversion and Distribution

Shuttle Background

Three buses are used to distribute the power generated by the three fuel cells. The buses are located in the forward, mid, and aft sections of the vehicle. Power and load controller assemblies via, remote switching, are used to manage the power outputs from each of the three fuel cells. The buses, in each vehicle section, are located near the major loads. Some electrical loads may receive power from two or three sources — not to obtain more power, but to provide redundancy. Continuity of power is another reason for utilizing multiple power sources — some subsystems being sensitive to power interruptions (Ref. 10.1).

Electrical inverters are used to provide power for alternating current loads. A total of 10 controllers are employed to operate the AC motors that power vent doors on the air data system, star trackers, and payload bay. Three controllers are located in the forward section of the Shuttle, two in the mid section, and three in the aft section. Payload bay door latches are also powered by AC motors. Controllers are also needed to operate motor-actuated RCS and OMS valves.

A total of 11,610 lb is identified as the weight of all items in the Electrical Power, Distribution, and control category. Out of this amount, 5,735 lb is identified as the weight of electrical cabling (Ref. 10.2). This includes cabling for both power and information circuitry.

WB-003 Concepts

On the WB-003 vehicle, wire cable and electric motors are substituted for hydraulic lines and hydraulic actuators. In addition, all information is transmitted via fiber-optics instead of by copper wire. The electrical distribution weights are vastly increased because of the substitution of electric actuators, but the elimination of the hydraulic lines nets an overall savings in vehicle weight. A symbolic representation of the arrangement of power cabling and fiber optics is shown in Figure 10.0. Dual bundles of cables are used for redundancy.

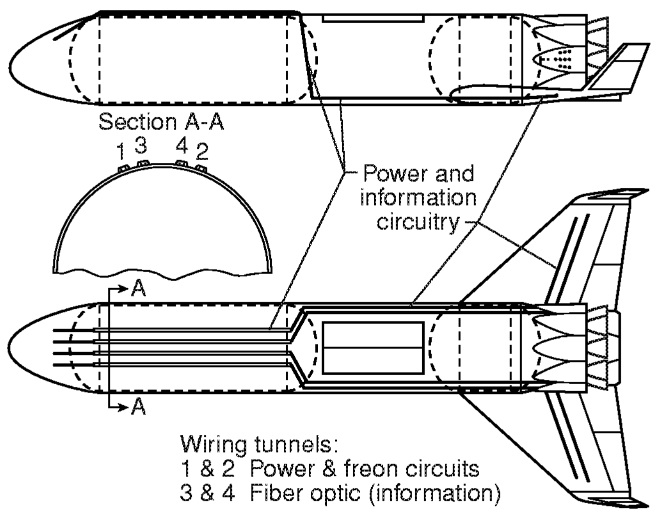


Figure 10.0. Avionics and power cabling (symbolic).

Electrical power, information cabling, and power controllers are listed in Table 17. Fiber optic cabling is also used for the safe and arm system (Ref. 10.3). Fiber optics and laser light energy control and power explosive devices. In so doing, the system is not sensitive to stray electromotive impulses as is the case for the more conventional hard-wired systems. Nineteen thousand feet of fiber optic cabling is used for health monitoring. This latter cabling is not equipped with protective layers of sheathing but is bonded to structure to monitor structural health. When listed only with its acrylate coating, the cabling weighs only 46×10^{-6} lb/ft (0.0685 grams per meter). Refer to Section 13.0, Table 22.

Table 17. Cabling and Power Conversion Weights

Item	Length, ft	Wt/ft	Total Wt, lb
Avionics power	900	0.360	324
Actuator power	5,520	0.722	3,790
Information circuitry (fiberoptic)	15,000	9.948	710
Safe and arm system (fiberoptic)	200	0.048	10
Cabling total			4,834
Power conversion equipment			700
56 motor controllers (for surface controls and engine gimbals)			784
Cabling total			6,318

56 motor controllers are required for the 14 actuators. Each motor controller weighs 14 lb and is approximately 8 in. × 8 in. × 12 in. (Fig.10.1). These values are based on fairly aggressive assumptions for advances in technology (Ref.10.4).

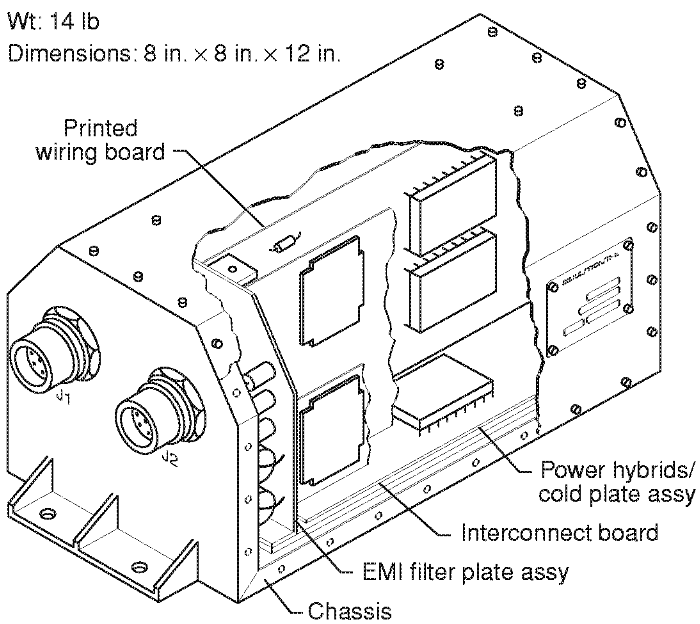


Figure 10.1. Electric actuator motor controller.

Motor controllers are located in the nose section of the vehicle with the avionics (Fig. 7.1). In so doing, the power supplied to the motors is conditioned at the power source, reducing by a modest amount the amperage (hence cable weight) supplied to the actuators. Some of the motor controllers are multipurpose being utilized as engine gimbal motors during ascent but for aero-surface control during descent.

References

10.1 Anon.: “Press Information — Space Shuttle Transportation System” prepared by Rockwell International, March 1982.

10.2 Anon.: “Space Shuttle Mass Properties Status Report” prepared by Rockwell International, July 1995.

10.3 McGrath, D. K.: “Electo-Optical Safe-and-Arm Presentation” private communication in the form of a fax from the Thiokol Corporation, Aug. 1999.

10.4 Telecon Mary Ellen Roth, Lewis Research Center, May 1999.

11.0 Hydraulic Conversion and Distribution System

Shuttle Background

The Shuttle has three, 3000 psi hydraulic systems, any one of which can generate, distribute, control, and monitor hydraulic fluid under pressure. The hydraulics on the Shuttle are used to operate all aerodynamic surfaces, main engine gimbals, deploy landing gear, and operate the nose gear steering (Ref. 10.1). A low pressure pump is used to circulate the hydraulic fluid while the shuttle is on orbit. The power source for the system is three hydrazine-fueled APUs driving hydraulic pumps. A water spray boiler is required to cool the system. The weight of the hydraulic power conversion and distribution system is 1,871 lb (Ref. 10.2).

WB-003 Concepts

The WB-003 vehicle does not utilize any systems requiring hydraulic power.

12.0 Surface Controls

Shuttle Background

The Shuttle has a single body flap, two sets of elevons, and a split rudder – the latter for directional control and energy management. Both the rudder-speed brake and the body flap are controlled by power drive units (PDUs). The PDUs are supplied with hydraulic fluid at 3000 psi from the Shuttle’s three APUs. Outputs from these PDUs are mechanical in the form of torques that are fed to rotary actuators on the control surfaces. The body flap is equipped with one PDU that supplies power by means of aluminum shafting to four rotary actuators. The rudder-speed brake system is equipped with two PDUs that supply mechanical power (also via aluminum shafting) to four rotary actuators. The PDUs condition and control shaft output speeds, but the rotary actuators provide the major gear reduction while serving also (mechanically) as hinges. The body flap system is ‘tri-electric-tri-hydraulic’ redundant. All four rudder-speed brake actuators have dual planetary gearing for independent or simultaneous rudder and speed brake operation. Each elevon is equipped with one quad-redundant actuator that is supplied directly with 3000 psi hydraulic fluid, no PDUs being required. Except for wing load relief, the Shuttle does not have to use its aero-surfaces during ascent.

WB-003 Concepts

Electric actuators are required for four elevons, two tip fin controllers, and one body flap, or a total of seven surfaces on the WB-003 vehicle. The tip fin controllers consist of single outward-displacing movable surfaces. The basic elements required for surface control operation are shown in Figure 12.0. (Electric actuation for the current Shuttle elevons was demonstrated by Swingle and Edge in the late seventies but was not adopted by the Shuttle program (Ref 12.1) — probably because of the added cost that the change would incur and the fact that the hydraulic system was flight proven and reliable.)

After reviewing the horsepower requirements (on the Shuttle) to perform both surface and engine gimbal actuation, it appears that a single size of actuator could be used. The horsepower estimates range from as low as 42 hp for one of the engine gimbals, to a high of 57 hp for an inboard elevon. If commonality is achievable, acquisition, inventory, and operational costs could be greatly reduced for the total of 21 quad-redundant-actuators required (i.e. seven surfaces and seven engines, the latter having two actuators on each engine).

Commonality may not mean commonality in mechanism in that actuator strokes and rates may have to be tailored to the particular function. The actuator selected for illustrative purposes is shown in Figure 6.2. The estimated deliverable power for each quad-redundant actuator is 58 hp. This is based on the assumption that four motors with mechanisms are operating at 17 hp each at a mechanical efficiency of 0.85. (Note: the quad-redundancy only applies to the four electric motor drives, the mechanisms being a potential sources for single point failure.) Each actuator requires four motor controllers (Fig. 10.1). Control surface information is sent back to the motor controllers in the nose section of the vehicle via fiber optics. By locating the motor controllers in the nose of the vehicle, the power supplied to the motors is conditioned at the power source, reducing by a modest amount the amperage (hence cable weight) supplied to the actuators. Some of the motor controllers are multipurpose being utilized as engine gimbal motors during ascent but for aero-surface control during descent.

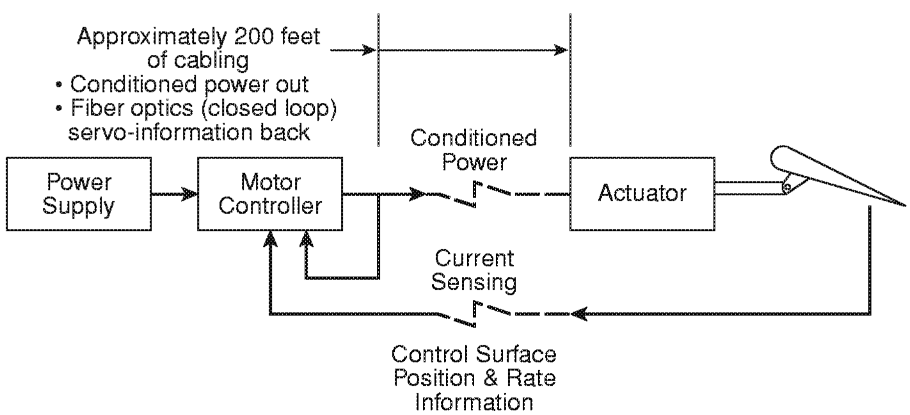


Figure 12.0. Actuator block diagram.

In Table 18, a basic 260 lb weight is obtained by adding 80 lb to the 180 lb actuator shown in Fig. 6.2. The extra weight is allocated for installation, linkages, and miscellaneous. The weight estimates for the two tip-fin controllers and the four elevons are merely multiples of the 260 lb figure. For the body flap, four actuators are connected in multiples by gearing configured for torque summing. An additional 300 lb is allocated for the torque summing gearing between actuators. The weights for the various actuation functions approximate the weights identified by the CONSIZ Program (Appendix B).

Table 18. Actuator Weights

Surface	No. of Surfaces	Motor Controllers		Actuators		Totals
		No.	Wt, lb	No.	Wt, lb	
Elevons	4	16	224	4	1040	1264
Tip fin controllers	2	8	112	2	520	632
Body Flap	1*	16	224	4	1340	1564
Total	7	40	560	6	2900	3460

*One surface, four actuators.

Reference

12.1 Swingle, W. L.; and Edge, J. T.: "The Electric Orbiter," Proceedings of the 1981 National Aerospace Electronics Conference, Vol. I, Dayton, Ohio.

13.0 Avionics

Shuttle Background

The Shuttle avionics system provides all the functions needed for guidance, navigation, and control; communications and tracking; data processing; and monitoring of operational and development flight instrumentation. Displays and controls are part of the avionics group. The avionics provides for the sequencing and control for the external tank and the two solid rocket boosters. Five central computers are used to provide fail-operational/fail-safe capability. Approximately 27 multiplexer-demultiplexers are used to manage information. The Shuttle has five general-purpose computers each with an input/output processing capability. Each unit weighs 65 lb (Ref. 13.1). The two mass memories each weighed 25 lb.

A core component in the avionics architecture is the air data system. This system is made up of two probes that are deployed to positions outside the Shuttle's heat shield on either side of the nose section. Each probe is provided with two motors equipped with differential gearing. Heaters are provided for deicing. The probe mechanism is thermally protected in the stowed position and, in the deployed position, the mechanical fittings match the outer moldline of the Shuttle.

The Shuttle 'Health Monitoring System' centers around a Caution and Warning System. This system notifies the crew by audio or visual means of any anomalous conditions in the operating systems of the Shuttle. The system gets 120 inputs directly from transducers located throughout the vehicle. A 40-light array on the flight deck and a 120-light array make up most of the visual displays. Audio signals are used to warn of smoke in the crew compartment, or a drop in cabin pressure. In addition to transducers, the caution and warning hardware includes master alarms, multiplexers, a comparator, computers, and a control logic unit. Computer keyboards, in some cases, can be used to change the limits for which caution and warning signals are given. In general, however, the astronauts are relied upon to diagnose problems as they arise based on various sources of information including the audio and visual signals provided above.

WB-003 Concepts

Introduction

The requirements for the avionics should be reduced over those for the current Shuttle simply because of the reduced number of elements involved. For example, there are no solid rockets or external tank to control and separate. Also, there is no requirement for a remote manipulator; however, such a device could be retrofitted as a mission-specific add-on. Also, there are no life support systems required of the WB-003 vehicle since the vehicle is unmanned.

The functional components required for the WB-003 avionics group are identified in Appendix A. The architecture must be such that the vehicle's flight and performance can be controlled and monitored by: 1) the vehicle's own computer; 2) mission control; 3) a crew in the module in the payload bay of the vehicle; or 4) a space station crew (during docking). In regard the latter, auto-docking by the vehicle to the International Space Station, it appears, will not be allowed.

Avionics Subsystems

Tentatively, three computers are used, each configured with fault-tolerant-architectures, to give fail-safe/fail-operational capability (Fig. 13.0). Three computers with fault-tolerant architecture (it is assumed) will provide the same redundancy as five computers without the special architecture.

Forward avionics are located on deck B in the nose section (Fig.7.1). This includes the three main computers, and flight-critical MDMs. Aft MDMs are installed in the intertank area and in the wing cavities in the vicinity of station x = 2400, y = 230 (Fig. 1.0). Most of the top deck in the nose section (deck A) is reserved for propellants for the forward RCS and for the reactants for the four 270 volt fuel cells. The principal avionics line replaceable units (LRUs) are listed in Tables 19-22 along with their weights, volumes, and power requirements.

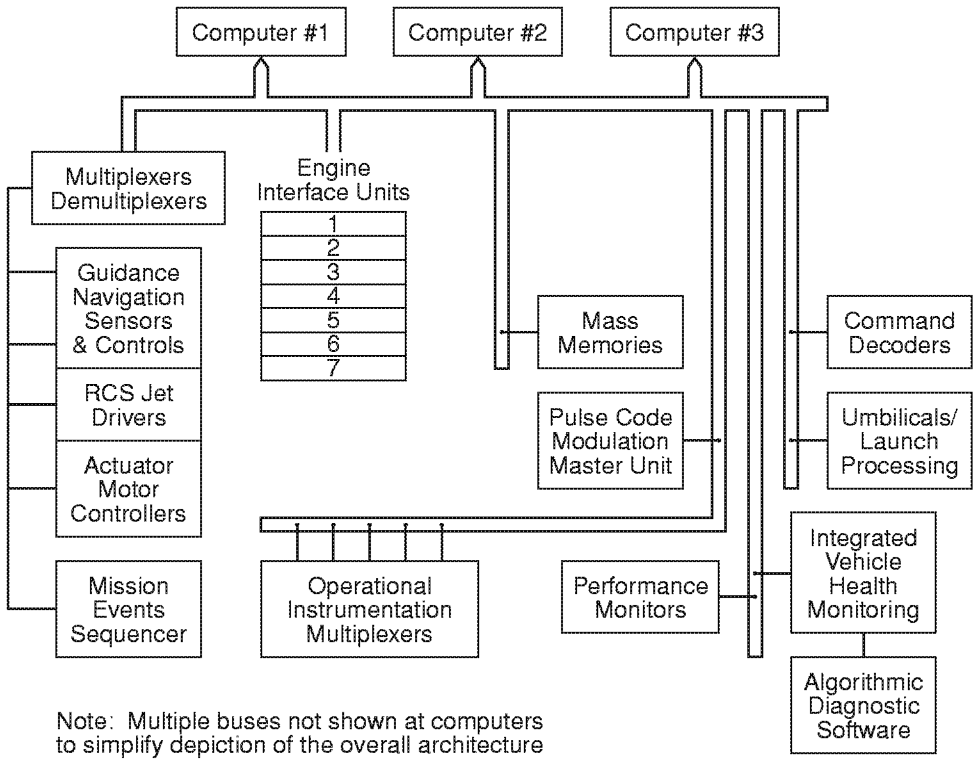


Figure 13.0. Data processing block diagram.

The cross-hatched volume in the nose section available for avionics is 810 ft^3. This is based on an assumed floor area of 135 ft^2 and a rack height of 6 ft. The volume required for avionics is 148 ft^3. This includes the volume required for eight MDMs. The final volume is based on a packaging efficiency factor of 0.25; the low value being used to allow for accessibility. The volume required for 56 controllers is 194 ft^3 based on a packaging efficiency factor of 0.48. These units are installed on either side of the central aisle (Fig. 7.1). (Note: there are seven movable aero surfaces and seven main engines on the WB-003 vehicle. Each engine has one yaw and on pitch actuator. For quad-redundancy, each actuator would have four motors and four controllers or eight controllers per main engine; or 56 controllers per vehicle. For the seven aero surfaces, 40 or more of the gimbal motor controllers would be rendered multipurpose for use on surface controls with an additional 16 controllers out of the 56 available as redundant units.)

Table 19. Guidance, Navigation, and Control

	Volume, ft^3	Unit Wt, lb	Power, Watts	No. Req'd	Wt, lb Total
UHF Transceiver	0.2	32	40	3	96
Beacon transponder	1.1	11	80	1	11
S Band telemetry (includes transmitter, receiver, antenna)	0.2	11	28	2	22
Inertial navigation unit	0.3	22	15	2	44
RCS jet drivers	2.0	40	40	2	40
Embedded air data system	1.0	25	20	2	50
					263
			Installation	19%	50
			Subtotal		313

Table 20. Communication and Tracking

	Volume, ft^3	Unit Wt, lb	Power, Watts	No. Req'd	Wt, lb Total
UHF Transceiver	0.1	17	7	2	34
Beacon transponder	0.1	1	5	1	1
S Band telemetry (includes transmitter, receiver, antenna)	1.2	76	228	1	76
Auto Docking System	0.8	50	150	1	50
Global positioning system receiver/transponder	1.25	69	112	1	112
					273
			Installation	19%	52
			Subtotal		325

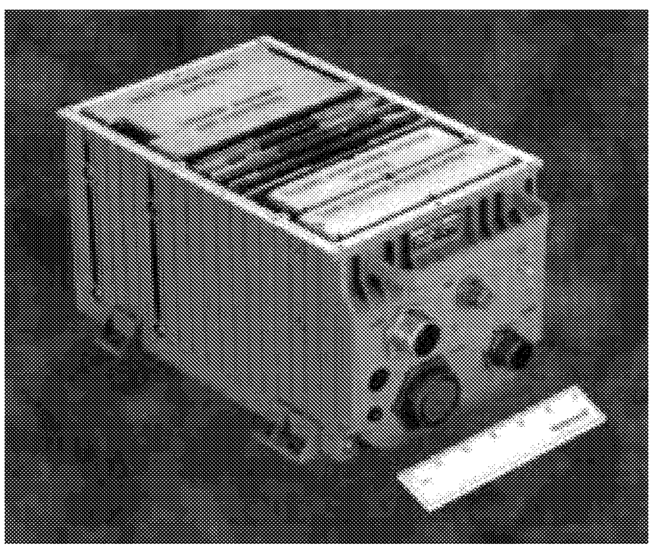
Table 21. Instrumentation Systems

	Volume, ft^3	Unit Wt, lb	Power, Watts	No. Req'd	Wt, lb Total
Sensors (Health monitoring)	n/a	60	25	n/a	70
Recorders (Solid State)	0.4	25	25	2	50
Master timing units	0.4	23	20	2	46
Signal conditioners	0.7	40	15	4	160
					326
			Installation	71%	231
			Subtotal		557

Table 22. Data Processing

	Volume, ft^3	Unit Wt, lb	Power, Watts	No. Req'd	Wt, lb Total
Computers	1.1	22	120	3	66
Multiplexers	0.4	12	30	14	168
Mass memories	0.3	14	15	3	42
					276
			Installation	19%	52
			Subtotal		328

An inertial navigation unit with embedded global positioning hardware (GPS) is shown in Figure 13.1. A flush air data system (FADS) is used to measure dynamic pressure, angle of attack, and sideslip (Refs. 13.2 and 13.3). Five niobium pressure plugs are strategically placed in the ACC nose cap of the vehicle. The niobium has a melting point that is in excess of 4000°F making it suitable for use in an environment that is not expected to exceed approximately 2500°F. Also the thermal expansion coefficient of niobium closely matches that of the ACC material. The system is estimated to weigh 50 lb. This includes five pressure plugs, power supply, and the electronics necessary to process the data and condition it for transmission to the vehicle's main computers.



Wt = 22 lb
Dimensions: 6 in. w × 8in. × 12 in. lg
(Honeywell)

Figure 13.1. Inertial navigation with imbedded GPS.

Integrated Vehicle Health Monitoring System (IVHM)

The focal point of an IVHM will be a Liquid Crystal Display (LCD) that will show right and lefthand side, front and rear, top and bottom views of the vehicle. Visualizations would be used to show graphically locations and nature of any anomalous conditions throughout the vehicle. Overtemperature would be shown in various gradations of red, hydrogen leaks in blue, oxygen in green; localized overpressure conditions would be shown as animated moving shock waves; localized failure in structure as discontinuities in the vehicle line drawings. In so doing, the overall general health of the vehicle could be monitored and trouble spots identified on a global basis. For a vehicle that is unmanned, the displays would be installed at ground control. For a vehicle with a manned module in the payload bay, displays would be available in the module as well as at ground control.

Overtemperature and overpressure could be measured using a cylinder approximately 3 in. in diameter by 4 in. long (Fig.13.2). A calibrated shear disc with spike would be installed in the front end of the cylinder. A thermistor would be installed on the outside of the disc.

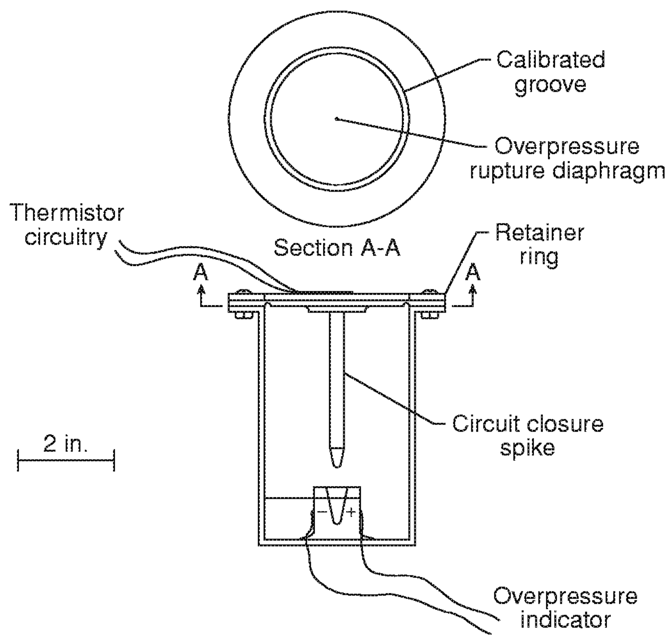


Figure 13.2. Overpressure and temperature sensor.

In the event of an overpressure, the disc would shear at a pre-determined overpressure driving the spike to close a circuit. The disc is grooved at a radius commensurate with the shoulder on the cylinder. The shape, depth, and micro-finish of the groove are carefully controlled to insure rupture at the prescribed overpressure. Fluctuating temperatures at ambient pressures would be indicative of a fire. An explosion would be characterized by a closure of the circuit with a short, steady temperature pulse, lasting perhaps microseconds. By placing hundreds of these devices all over the vehicle, and particularly in compartments where LOX and LH are stored, it would be possible to identify trouble spots.

For additional structural health monitoring, fiber optic cables would be bonded to all the major structural components (Ref. 13.4). The cables would be bonded to the exterior face sheets of the composite LH tank and to the exterior surface of the AL-Li LOX tank. Thirty-six strings would be used on each tank, installed in the axial direction in zig-zag patterns. The starting points for each string would be placed circumferentially at 10° spacings. Thirty-six strings would be used for each barrel section, and each dome, making a total of 108 strings per tank; or 216 strings for two tanks. The same fiber optics cabling would be bonded to the inside of the nose, mid-body, aft-body and wings. Sixteen strings (each) would be placed on the thrust structure; around inside of the nose section, mid-body. Each wing would be equipped with 16 strings, installed spanwise with diminishing spacing from wing root to tip. Using the bonded fiber optic strings bi-axial stresses at 14 points are measured for each string. Estimates for the component weights of a health monitoring system are given in Table 23.

Techniques have also been developed for detecting both LOX and LH leaks using fiber optics. This is achieved by adding palladium patches in contact with the fibers at selected stations for hydrogen leaks. Gold patches on the fiber optics are used to detect oxygen leaks. Since strain can be measured, it is also possible to measure dynamic response. A lowering of frequency with time is indicative of aging of a composite structure since, with time, microscopic failures occur within fibers and in between fiber layers in shear, yielding a lower modulus.

When totaling the category weights for avionics (Tables 19-22), it was found that this total exceeded the allocated amount of 1,413 lb (Appendix B) by 209 lb. This overrun, compared to that allocated, is primarily due to the bonding agent allowance shown in Table 23 and incorporated into Table 21 as "installation" weight in the amount of 71 percent of the category weight.

If the fiber optics could be imbedded in the composite structure, most of the weight allocation for external bonding could be eliminated. This, of course, does not apply to the Al-Li tank, for which embedding is not practical.

Algorithms would be incorporated into the health monitoring software. For example, both rocket engine chamber pressure and overall vehicle velocity change could be combined to form a consensus of engine performance. Other diagnostic information might include engine supply pressures, turbo-pump rpm, and internal temperatures and pressures. By using algorithms and taking a consensus, confusion caused by an errant 'red light' might be avoided. Further, the diagnostic capability of the system should speed up the identification of potential vehicle problems.

Table 23. Health Monitoring System Weights

Item	Wt, lb
19,500 ft of 125 micron diameter fiber optic cabling with acrylate coating*	1
Bonding agents (fiber to structure)	202
25 overpressure temperature units @ 0.76 lb ea	19
	222

*0.0685 grams per meter (unit cable weight per telecon Dr. R.S. Rogowski, 8/99 LaRC)

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14.0 Environmental Control

Shuttle Background

The Shuttle has two 7.5 ft × 30 ft forward-deployable radiator panels and two aft-fixed radiator panels of equal size. The panels are mounted on the inner surface of the payload bay doors. A flash evaporator is used to accommodate peak thermal loads and to provide a means of heat rejection until the payload bay doors are opened on orbit. In the event that the payload bay door opening is delayed, the flash evaporator alone is used for heat rejection. The flash evaporator can maintain proper temperature in the orbiter for 6 to 8 hours on 200 to 300 lb of water. The door panel radiators are capable of rejecting 77,635 Btu/hr, the flash evaporator 130,000 Btu/hr.

The principal method for heat transport is via freon loops. However, because of its toxicity, the freon is exchanged with water loops for all of the cabin cooling requirements. A schematic of the Shuttle system is shown in Figure 14.0. The Shuttle has three clusters of cold plates. One set is located in the nose section, one in mid fuselage, and one in the aft body. The Shuttle is also equipped with an ammonia boiler system for heat rejection during entry below 100, 000 ft. However, flight experience has shown that the system is not needed during reentry. It is used, however, on the ground, for approximately one-half hour, until ground service trucks are connected.

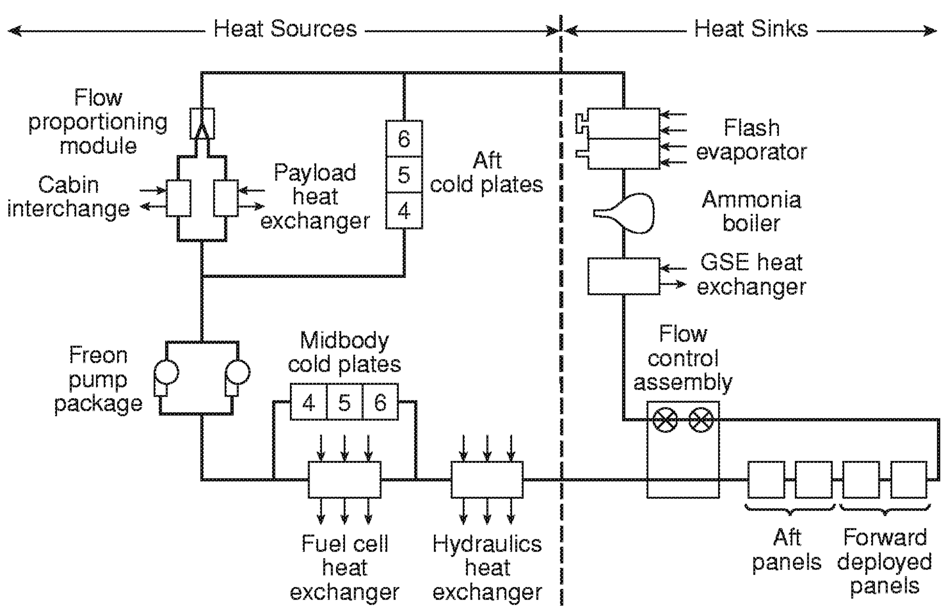

Figure 14.0. Shuttle active thermal control system.

WB-003 Concepts

The WB-003 vehicle's transport loop consists of freon only; there being no requirement for a water loop for a crew cabin (Fig. 14.1). A Shuttle flash evaporator is used to accommodate peak heat loads and heat rejection when the payload bay doors are closed. Shuttle-type radiators are installed in the payload bay doors for average heat loads. A connection to the flash evaporator system is provided for the crew module when it is inserted in the cargo bay.

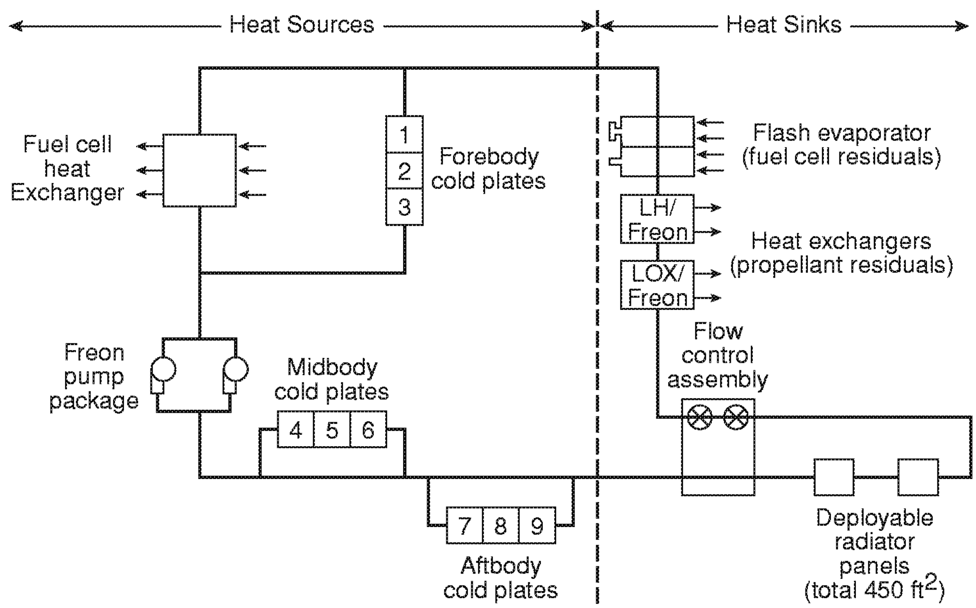

Figure 14.1. WB-003 active thermal control system.

One freon pump and numerous heat exchangers, controls, and cold plates are used for heat transport. Two examples of heat transport equipment needed are shown in Figs 14.2 and 14.3, namely a fuel cell heat exchanger and a freon pump package.

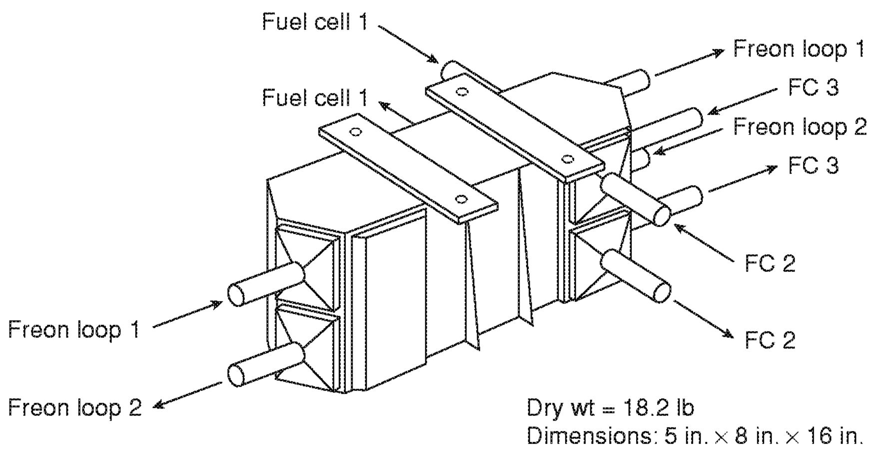

Figure 14.2. Fuel cell heat exchanger.

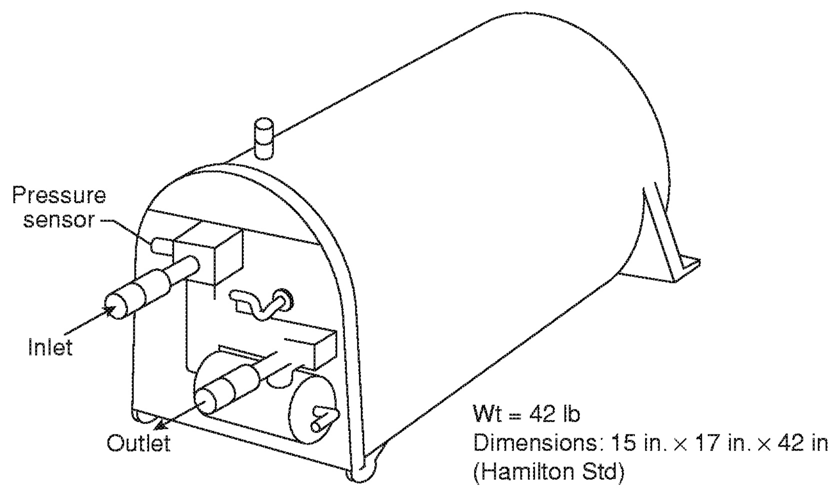

Figure 14.3. Freon pump package.

Principal differences between the Shuttle thermal control system and that for the WB-003 vehicle are as follows:

- The freon-to-water cabin interchanger is not needed in an unmanned vehicle.
- Only about half as much area is available for radiators on the 35-ft payload bay doors.
- The ammonia system installed in the Shuttle system is not used because the heat sink capacity of the active control system is sufficient for carrying the vehicle through the reentry heat pulse. It is also assumed that the WB-003 vehicle would also not need an ammonia system.
- Since there are no hydraulics on the new vehicle, there is no need for a hydraulics heat exchanger.
- There is no need for an oxygen/nitrogen supply and revitalization system. Thus CO_2 cartridges, gas controllers, cabin fans, etc. can be eliminated for the unmanned vehicle.

- Residual and vented propellants are utilized for supplementary cooling on the WB-003 vehicle in order to reduce the fluids inventories that would otherwise be carried (Fig. 14.1).

The flash evaporator and the three heat exchangers are all located in the casual space between the aft dome of the LH tank and the payload bay doors (Fig. 6.4). The fuel cell heat exchangers and the pump packages are located in the forebody on Deck A (Fig. 7.1). Two freon lines are installed in the power tunnels — one for freon supply and one for return (Fig. 10.0). The environmental control system weights are identified in Table 24. The LH and LOX exchangers are included under flash evaporator weights.

Table 24. Environmental Control System Weights

Item	Wt, lb
Equipment cooling	559
Heat transport loop	1451
Radiators	285
Flash evaporators	266
Total	2561

70.0 Concepts for Servicing and Inspecting Main Propellant Tanks

In general, the size, location, and arrangement of subsystems are critical factors in determining relative maintainability and reliability of any shuttle-like vehicle. Task times and manhours for scheduled and unscheduled maintenance on the current Shuttle are identified for most of its subsystems in Reference 70.1. From this data, the more labor-intensive maintenance operations can be identified.

Unfortunately. improved maintainability and weight reduction may be at cross-purposes. The number of access panels, vent doors, and other openings on an operating vehicle is shown in the current orbiter Shuttle Crash and Rescue Manual (Fig. 70.0 from Ref. 70.2). A logical goal, from the standpoint of cost and weight reduction for a new vehicle, would be to reduce the number of accesses, if possible.

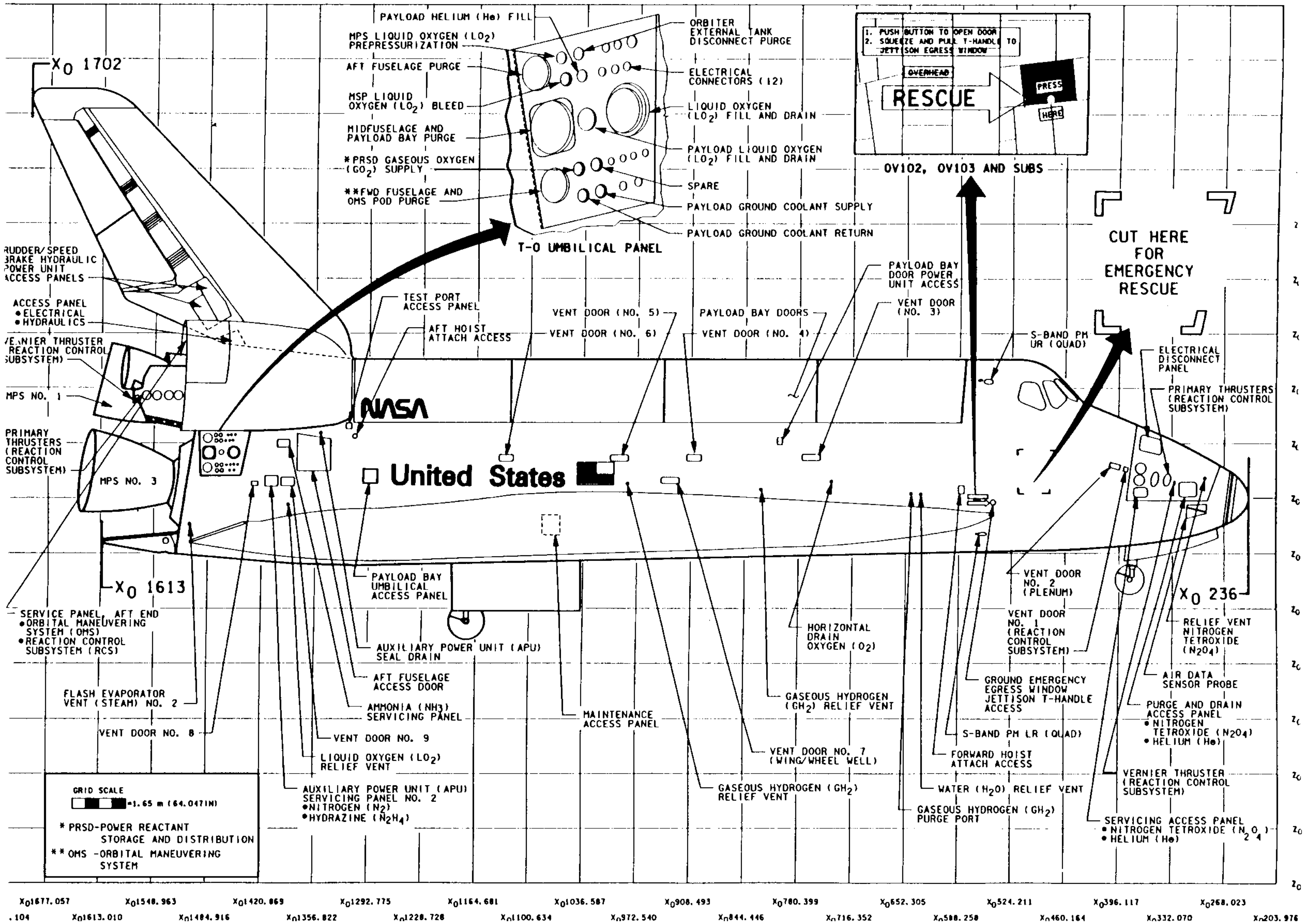

Fig. 70.0 Shuttle access panel inventory (from Ref. 14.1).

An inspection of the heating rates on a circular body vehicle shows that the heating rate in the payload bay area at the 4 o'clock and 8 o'clock positions is about twice that of a location just above the vehicle centerline (Ref. 70.3). Conventional wisdom suggests that there would be less risk of failure of the thermal protection around the access when the access is located in the lower heating regions. In addition, the weight of the cutout with seals and TPS would be lower.

An exception to the centerline rule is the location of the manned access panel in the engine compartment area (Fig. 70.1). Isotherms from Reference 70.3 show that heating rates, just above the wing, are very low and more indicative of the 'above-centerline' values.

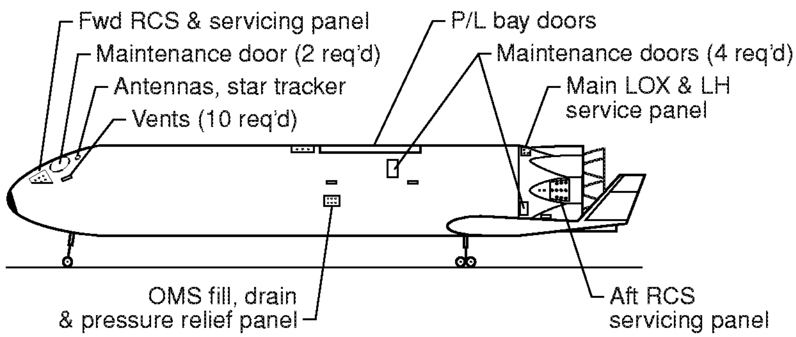

Figure 70.1. Maintenance and servicing panels.

Some type of system is needed for the inspection of the inside of the main propellant tanks. One approach might be to inspect the tanks while the vehicle is in the horizontal position (Fig. 70.2). This could be achieved by using a gantry-mounted-telescoping arm. Inspections could be manual or automated. For a manual inspection, technicians would ride in the gimbaled bucket, entering the tanks through the 8-ft diameter hatches provided.

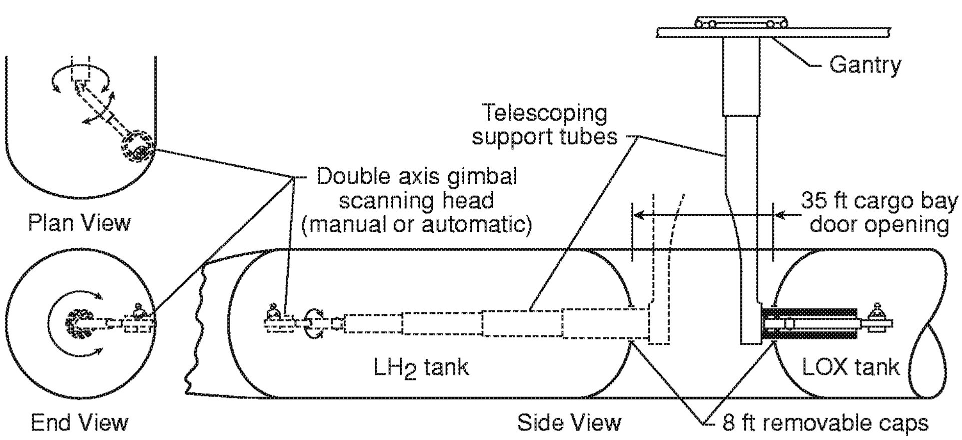

Fig. 70.2. Main tank inspection.

These hatches would be sealed with a cover similar to that used on the aft dome of the Shuttle's external LH tank (Ref. 70.4). This tank cover is 3-ft in diameter and is secured with 92 fasteners. For the same spacing circumferentially, 245 fasteners would be needed for an 8-ft cover plate (Fig. 70.3). Since the LOX access cover is on the forward end of the WB-003 vehicle, fortuitously it would not be subjected to the much higher pressures characteristic of a dense fluid subjected to axial acceleration loads.

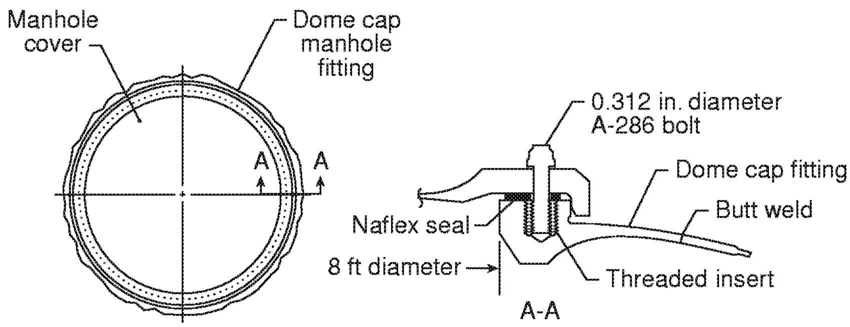

Fig. 70.3. LOX and LH_2 manhole cover design.

For an automated inspection of the LH tank, a head equipped with an ultrasonic scanner (or other nondestructive system) would traverse the entire interior of the tank looking for flaws or delaminations. Approximate head position could be pre-programmed, as well as expected images for a previously qualified tank. A computer would be used to automatically stop the inspection process when discrepancies of a given magnitude are identified in the tank structure. This would be followed by a manual inspection.

In order to accommodate unexpected thermal or mechanically induced tank deflections, the sensor head could be mounted in a carriage which, in turn, is mounted on casters that are spring loaded to accommodate uncharacteristic distortions. These casters would roll along the inner facesheet of the honeycomb sandwich tank shell. Since the LH tank has no internal ring-frames or stringers, the inspection process is facilitated.

For the Al-Li LOX tank, the telescoping arm would be pre-programmed for global displacement based on the ring-frame and stringer geometries from electronically developed drawings. Macroscopic tank distortions (thermal or mechanical) would be accommodated by a laser transit mounted near the sensor head. The inspection of the metallic (Al-Li) tank could be accomplished using X-rays and the results compared with a qualified tank. Like the procedure for the LH tank, a computer would stop the inspection at those locations for which expected and actual images differed. The sensor head could also be guided by grooved rollers that run on selected stringers or ring frames. Radiographic and electro-magnetic methods for nondestructive testing are described in Reference 70.5.

The outside of the tanks would be difficult to inspect. One possible approach for partial inspection might be to view the tanks using infrared camera imaging while the tanks are cooled inside using gaseous nitrogen, or after the tanks are fueled with LH and LOX. Infrared images obtained would be compared with tank installations known to be qualified. Visual and optical methods of testing are described in Volume III of Reference 70.5. Other methods that would be used depending on circumstances include leak (pressure decay), acoustic, and liquid penetrant. By utilizing both internal and external scans, the accuracy of the evaluation of tank integrity would be enhanced. Infrared imaging, at fairly low resolution, would be used — such as a field of view that included the entire vehicle. Anomalous thermal patterns showing up in the imagery (scanned visually and by a computer) would provide hints of LH or LOX leaks.

The main engine power heads, gimbals, pressurization, purge, and other systems can be serviced from within the thrust cone. The opening between slant struts is 42 in. at the base end of the cone and 60 in. at the forward end leaving ample room for engine access by a technician from within the vehicle. For main engine access from a position outside the vehicle, one or more of the seven engine fairing segments could be removed by removing 22 fasteners (Fig. 3.2). The aft RCS engines are accessible from the inside of the fairing at the 3 o'clock and 9 o'clock engine pod locations, or by removal of fairing segments. Two elliptical maintenance doors are provided in the nose section. The minor axis of the doors is 4 ft, the major axis 8 ft. The doors are pivoted about an axes parallel to, but offset slightly from the minor axes.

In the event of an unwarranted overpressure in the nose section, the doors would open to a predetermined position limited by a linkage system. The pivot axis offset would be such that the trailing edge of the door opens outward, the leading edge inward. The doors would also be removable to allow for initial installation of systems, or for extensive ground maintenance. Four additional maintenance doors are provided. Two are located in the payload bay area and two in the main propulsion system compartment. These doors are 3 ft 6 in. wide by 6 ft high (Fig 70.1).

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Comments

As stated in the introduction, the mass properties, as provided in Appendix B, were utilized as much as possible in developing the vehicle to be used as a guide in operational studies. However, it is believed that a re-assignment of some of the weights (in particular, to structure) would result in an improvement in the vehicle model. For example, the weight allowances made for the flash evaporator water supply and the landing gear in Appendix B appear to be conservative. However, the allowances for structure appear to be non-conservative, particularly for the main propellant tankage. It is suggested that the shortfall in structural weight allocations might be partially restored by:

- Application of innovative ways for reducing the amount of residual, reserve, and inflight propellants lost. As an example, propellants that are normally just vented to the atmosphere could be used for cooling (Fig. 14.1).

- Reduction in the amount of reserve propellants through re-evaluation of the missions and margins.

- Reduction in the amount of secondary structure through re-evaluation of the number of vent and service doors needed.

- Application of composites to landing gear and the elimination of hydraulic fluid through the substitution of pneumatics for shock attenuation.

- Elimination of the conventional braking system and the substitution of some type of ground arrestor or parachute to provide all of the braking.

- Reduction in the number of redundant subsystems, particularly in the actuation systems specified for the engine gimbals.

- Analytic solutions for the main propulsion thrust structure may yield lower weights than those shown by the CONSIZ Program. Current mass estimating relationships were derived from the more complex Shuttle thrust structure.

Overall, the information contained herein just barely "scratches the surface" in the definition of subsystems. In addition, there are many unresolved issues. For example, are fuel cells (as suggested by Appendix A) the best source for a high-voltage supply for actuators? In regard to thermal protection, are the large molded "C-sections" used for wing and tail on the Shuttle and identified for the WB-003, the best choice or would individual rigid tiles installed on a composite substrate be the best system based on acquisition costs? Based on life-cycle costs, would the multi-tile leading edges be the viable option? (Ref. a presentation at NASA-LaRC by Howard Goldstein NASA-Ames April 1989.)

In regard to structure, the modelling of structure based on weights allocated is, at best, preliminary and conceptual. The report (text and appendices) should, however, provide a better view of the weights assumed when compared to the Shuttle and the present status of materials and related technologies.

Still another issue is the impact of structural weight (robustness) on life-cycle costs. By utilizing extremely lightweight structures, payload capability is enhanced but maintenance costs will go up because of increased vulnerability to casual and operational damage.

All of the above are issues requiring greater depth of analysis and have not been addressed in sufficient depth in this report to the extent that rational conclusions can be drawn. One underlying issue is that a single stage, not burdened with drop tanks or boost stages, should be much simpler and less costly to operate.

Acknowledgements

The author is always responsible for his own mistakes. This report is by no means perfect. Keeping these factors in mind, the author wishes to thank the following reviewers for their comments:

	Roger A. Lepsch, Jr.	LaRC
	W. Douglas Morris	LaRC
	David E. Myers	LaRC
and especially	A. C. Costa	NCI Information Systems

Also the following persons have, over a considerable length of time, provided useful technical data that supported this current effort:

Discipline	Individual	Affiliation
Structures	Wayne Sawyer	LaRC
	Jim Robinson	FDC/NYMA
	Bob Davis	LaRC
	Brian Jensen	LaRC
	Erik Weiser	LaRC
Materials	Tom Bales	LaRC (ret.)
	Bland Stein	LaRC (ret.)
Thermal Protection	John Shideler	LaRC (ret.)
	Ron Banas	Lockheed/Sunnyvale
	Kay Wurster	LaRC
	Neale Kelly	LaRC (ret.)
	Don Curry	JSC
Mass Properties	Buddy Heineman	JSC (ret.)
	Wayne Peterson	JSC
Tanks	Tom Freeman	LaRC
	Ed Hooks	Lockheed/Michoud
Landing & Auxiliary Systems	Bob Daugherty	LaRC
	Tom Yager	LaRC
	Carlisle Campbell	JSC
Main Propulsion	Jim Martin	Boeing/Downey
Abort Systems	Mike Lara	Thiokol/Elkton
	David McGrath	Thiokol/Elkton
	Dean Jorgensen	Pioneer Aerospace

Auxiliary Propulsion	Steven Schneider	LeRC
	John Wanhainen	LeRC
	Paul Herr	LeRC & NASA HQ (ret.)
	Carl Stechman	Marquardt/Van Nuys
Power	John Giltner	Eagle-Picher
	Henry DeRonck	International Fuel Cells/Windsor Conn
	Clyde May	LaRC (ret.)
Power Conversion	Jim Nickerson	Maxwell Industries/San Diego
Pyrotechnics	Larry Bement	LaRC
Surface Controls	Mary Ellen Roth	LeRC
	J. T. Edge	JSC (ret.)
	Duane Teske	Sundstrand
Systems Integration	Hugh Davis	Davis Aerospace/TX
Health Monitoring Systems	Bob Rogowski	LaRC

Appendix A: WB-003 Vehicle Description

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November 1998

Winged-Body SSTO Rocket Vehicle Description

Consideration was given to ground and flight operations from the outset of the vehicle design and subsystem selection. Many of the evolutionary technology advances employed on the single-stage vehicle contribute to significant weight reductions and performance benefits over the current Space Shuttle; however, a large portion of this weight savings has been applied to aspects of vehicle design that enhance the operability, reliability, and safety of the system. Hydraulic systems are replaced with all-electric systems employing electromechanical actuators for engine gimbals and valves, aerodynamic surface controls, and landing gear. Toxic hypergolic propellants in orbital maneuvering and reaction control systems are replaced by cryogenic hydrogen and oxygen, providing commonality of propellant type with the main propulsion system. Auxiliary power units (APUs) are replaced with LH2/LO2 fuel cells. These advancements allow the design of an all-electric, all-hydrogen-fueled vehicle. The main engines would utilize integrated health monitoring, controller advancements, built-in test equipment, and single-cast construction to reduce welds wherever possible. The advanced avionics employed are lighter, more powerful, and can help decouple the vehicle from a majority of ground-based mission control functions, thus introducing a significantly higher level of autonomy. Subsystems that are fault-tolerant and possess built-in test equipment to monitor system conditions are essential for streamlined operations, especially in the propulsion system. Subsystem units, where feasible, are of a modular design for easy removal and replacement. A durable TPS is employed that is easy to remove and replace. Allowing for single engine fail-safe capability during the ascent trajectory enhances vehicle and passenger survivability. The use of standardized payload canisters with common vehicle interfaces allows off-line processing of payloads, thereby greatly streamlining operational procedures.

Subsystem Description

The following section describes each of the subsystems of the reference winged-body SSTO vehicle. The labeling is consistent with the reference weight breakdown statement (WBS).

1.0 Wing

A graphite-polyimide (Gr-Pi) composite is used as the primary structural material for the vehicle wing. The wing structural internal elements are kept to a minimum number of parts. The basic wing structure consists of forward and aft spars and a minimum number of ribs. A gear well is provided in the bottom of each wing at the wing/body intersection. Upper and lower wing skin covers are of a honeycomb sandwich construction. The wing leading edge is constructed of advanced carbon-carbon (ACC). The wings are joined by a graphite-epoxy (Gr-Ep) composite carrythrough structure that passes through the vehicle's aft skirt, just under the aft dome of the LO2 tank. A fairing between the wing and body is constructed of Gr-Pi.

Two elevon control surfaces are used on each wing. The surfaces are made of advanced carbon-carbon (ACC) in a hot structure design without externally applied thermal protection. In order to reduce control surface installation weight, cost, and complexity, no hingeline panel seals are used. The flow of hot gases are instead arrested by rub seals internal to the wing control surface assembly.

2.0 Tail Group

Wing tip fins are used in lieu of a fuselage mounted tail. During entry, tip fin controllers are used for yaw control to lessen the RCS propellant requirements. The structure is an ACC hot structure design with internal insulation and an insulated connection to the Gr-Pi wing. The control surfaces are hinged ACC split flaps that act as speed brakes for landing.

3.0 Body

The body is defined by three categories: basic or primary structures, propellant tanks, and secondary structures. The body utilizes an integral propellant tank arrangement.

Basic Structures

There are four basic structural sections for the winged-body vehicle -- the nose section forward of the hydrogen tank (excluding the ACC nosecap), the intertank section between the hydrogen and oxygen tanks, and the section aft of the oxygen tank, including the main engine thrust structure. Honeycomb sandwich Gr-Pi composites are used for the nose section, intertank, and the aft body section. The sandwich structures are stiffened by Gr-Pi ringframes. The thrust structure utilizes stiffened-skin Gr-Ep with aluminum-lithium truss members and joints to provide multiaxial strength.

Propellant Tanks

The reusable liquid hydrogen tank is constructed of Gr-Pi while the reusable liquid oxygen tank is constructed from aluminum-lithium 2195. Both tanks are internally stiffened by ringframes and stringers. Aluminum-lithium skirts are utilized on the ends of the oxygen tank cylinder to provide a thermal gradient sufficient to allow attachment of the Gr-Pi structures to a warm aluminum-lithium structure. Structurally, the tanks are integral with the body and carry the principal thrust/inertial loads. The tanks have a circular cross section and utilize elliptical end domes. Both the liquid hydrogen and oxygen tanks are insulated with Pmi foam insulation. It is expected that periodic inspection of the tanks would take place internally, but periodic use of external monitoring devices would provide early indications of cracks and leaks. For purposes of sizing the propellant tanks, an ullage factor of 3 % is used for both the hydrogen and oxygen tanks.

Secondary Structures

Included in this category are the payload bay structure, the payload canister, the payload bay doors and hardware, the base closeout structure, the main engine fairings, the aft OMS/RCS pods, and the fuselage body flap.

A payload bay frame structure is a permanent part of the winged-body vehicle structure. It consists of Gr-Ep members to support a 15 x 15 x 35 ft payload canister system that is installed just prior to flight.

The payload canister is a stiffened 15 x 15 x 35 ft box constructed of graphite-composite honeycomb panels. The payload is contained internal to the canister and is attached to a graphite composite cradle that is mounted on rails. The canister is processed off-line and is integrated to the vehicle just prior to flight by sliding the canister on rails. Each canister could be outfitted differently; however, standard interfaces are provided for power, environmental control, and venting.

The payload bay doors are constructed of stiffened Gr-Pi honeycomb panels, to which TABI blanket TPS is bonded.

The fuselage base closeout is fabricated from a Gr-Pi honeycomb structure, to which TABI blanket TPS is bonded.

Fairings constructed of Gr-Pi are located on the aft body to smooth the flow of air around the main engine powerheads. Pods containing the OMS and the aft RCS are located on both sides of the aft body. The pods are constructed of Gr-Pi honeycomb outer panels and internal framing.

The body flap is made of advanced carbon-carbon (ACC) in a hot structure design, without externally applied thermal protection, similar to that used for the elevons.

4.0 Environmental Protection

The thermal protection system (TPS) employs mainly reusable blanket materials that are bonded to the Gr-Pi vehicle structure or to the cryogenic tank insulation using silicon RTV adhesive. The fuselage nose cap, wing leading edges, and control surfaces of the vehicle use advanced carbon-carbon, the remaining regions use tailorable advanced blanket insulation (TABI). TABI is a woven fabric under study at the NASA Ames Research Center with fluted cores to add strength against aerodynamic buffeting. The TABI utilized has alumina insulation and silicon carbide surface fabric. High temperature felt strips are installed underneath the TPS panels and around the fasteners. Fasteners are made from low-conductivity, high-strength materials such as titanium. Gap fillers are utilized to prevent hot gas penetration. Both the blanket sections and advanced carbon-carbon panels vary in shape, area, and thickness over the vehicle depending on maximum local heating rates, heat loads, dynamic pressures, and the expansion coefficient of the material used.

Internally, insulation consisting of multilayer and bulk fibrous blankets are applied to the equipment and payload bays. The blankets are the same as those used on the current Space Shuttle.

A purge, vent, drain, and hazardous gas detection system is provided. The system performs an air purge while on the ground to thermally condition components and prevent hazardous gas accumulations. It vents compartments during ascent and descent to minimize differential pressure and also drains trapped fluids.

5.0 Landing Gear And Auxiliary Systems

The landing gear for the winged-body vehicle is of a tricycle-type consisting of a wheeled nose gear forward of the vehicle center-of-gravity and two wheeled main gear aft of the winged-body vehicle landing center-of-gravity. The gear have been sized for a landed weight based on empty propellant tanks and are modeled after those employed by the Space Shuttle. A small weight reduction is assumed based on the use of organic composite and metal matrix composite materials. The forward landing gear are housed in the nose region, and the aft gear are housed in the wings near the fuselage.

6.0 Main Propulsion

The main propulsion system for the winged-body vehicle consists of the main engines, a feed system, a pressurization system, engine gimbals, engine-mounted heatshields, and a pneumatic system.

The main engine system of the single-stage vehicle consists of seven RS-2100 oxygen-hydrogen engines. The RS-2100 is an engine concept under study by Boeing's Rocketdyne Division. It is a full-flow, staged-combustion-cycle engine with a fixed bell nozzle. Chamber pressure of the RS-2100 is similar to that of the SSME at 3,250 psi, and it has roughly similar performance. The high-pressure turbopumps utilize hydrostatic bearings for high life and reliability. The high-pressure pumps are driven by mixed preburners where the oxygen pump is driven by an oxygen-rich preburner and the hydrogen pump is driven by a hydrogen-rich preburner. Mixed preburners eliminate the need for inter-propellant seals in the pumps, thereby improving safety. To simplify the engine, the low-pressure turbopumps utilize a jet pump design with no moving parts. The main combustion chamber is a design based on the Universal Main Combustion Chamber being developed for the Block III SSME. The injector to the combustion chamber is a gas-gas co-axial type. The nozzle is constructed from A286 tubes and a titanium honeycomb jacket. Electromechanical actuators are used for sector valves. Other features include integrated health monitoring and a Block III controller.

The feed system is based on the propellant requirements of the main engines and is similar to the current Shuttle system. Materials are steel and aluminum. The pressurization system is also similar to the current Shuttle system and uses gases tapped from the main engines to pressurize the propellant tanks. Engines are gimbaled to control the vehicle during ascent using electromechanical actuators. The engine-mounted heat shields are similar to those used on the Space Shuttle.

A helium pneumatic system is used for the emergency actuation of engine and feed system valves. It also serves as a purge system to prevent the accumulation of hydrogen or oxygen gases in the vehicle during flight. Titanium-lined, Kevlar wrapped, high-pressure tanks are utilized for helium containment.

7.0 Propulsion, RCS

The reaction control system (RCS) for the winged-body vehicle is used for all attitude control functions while on orbit and during the entry phase of the mission. The system is divided into two modules aft and one forward on the vehicle fuselage. The pressure-fed RCS engines utilize liquid oxygen and hydrogen. The RCS engines have a 150-psi chamber pressure, an expansion ratio of 22, an effective vacuum specific impulse of 422 sec for on-orbit control and an effective impulse of 410 seconds during entry. The reaction control system uses 18 870-lb primary thrusters and 21 50-lb vernier thrusters. The oxygen is contained in vacuum-jacketed 718 Inconel tanks, and the hydrogen is contained in vacuum-jacketed 2219 aluminum tanks.

The OMS/RCS system layout and weights are consistent with Option 4 in "Integrated Hydrogen/Oxygen Technology Applied to Auxiliary Propulsion Systems", NASA CR-185289, prepared for Lewis Research Center by Rockwell International.

8.0 Propulsion, OMS

The orbital maneuvering system (OMS) is located in aft body pods. It is used for the primary orbital maneuvers conducted during the mission, including orbital transfer to the space station, rendezvous, and deorbit. The pump-fed expander cycle OMS engines utilize liquid oxygen and hydrogen. The OMS engines have a 800-psi chamber pressure, an expansion ratio of 100, and an effective vacuum specific impulse of 462 seconds. The orbital maneuvering system uses two 6000-lb thrust engines. Item 29.0 below details the OMS propellant budget breakdown. The oxygen is contained in vacuum-jacketed 718 inconel tanks, and the hydrogen is contained in vacuum-jacketed 2219 aluminum tanks.

The OMS/RCS system layout and weights are consistent with Option 4 in "Integrated Hydrogen/Oxygen Technology Applied to Auxiliary Propulsion Systems", NASA CR-185289, prepared for Lewis Research Center by Rockwell International.

9.0 Prime Power

The prime power system consists of fuel cells and dewars to hold the fuel cell reactants. The electrical power for the winged-body vehicle will be supplied by four 270-volt DC high-power-density LH2/LO2 fuel cells. These will be 80-kW cells. During ascent, it is estimated that 240-kW at 270-volts are required. During on-orbit operations and entry, the power demand should be less than 30 kW; hence, two of the fuel cells will be shut down once the vehicle is in orbit. Operation of the winged-body vehicle would be on internal power during ground checkout and launch pad holds.

10.0 Electrical Conversion and Distribution

The electrical conversion and distribution (ECD) system of the winged-body vehicle utilizes 270-volt DC. The conversion to lower voltages or to AC will be done at the component level or for particular power busses. The ECD system feeds power from the fuel cells to the avionics and all electromechanical actuators using copper cabling. To reduce weight, fiber optics are utilized for avionics command and signal functions.

Wiring installation non-optimums are reduced by using such lightweight materials as pultruded (non-conductive) fire-retardant composite materials for wiring harness trays and support brackets.

11.0 Hydraulics

No hydraulics are used on the single-stage vehicle.

12.0 Surface Control Actuation

Elimination of hydraulics is essential for reducing ground operation time and manpower. High-energy, rare-earth, samarium-cobalt brushless DC motors are used for all surface control applications including elevons, tip-fin controllers, body flap, and engine gimbals. The actuator elements include the controller, motor, and the mechanical drive. Control surface actuation must fail in the null position with the necessary control system fault-tolerant architecture for vehicle operation with one surface inoperable.

13.0 Avionics

The avionics subsystems are categorized as navigation, communications and tracking, instrumentation and data processing. The installation hardware weight allocations for such items as racks, cabinets, and shelves are based on the assumption that advanced materials and methods are used. These include composite sandwich construction for shelves and cabinets, and pultruded or molded composite sections for racks and frame structure.

The latest advances are incorporated into the avionics systems. Both power requirements and weight are critical to the overall launch system weight. Included in the avionics are technologies such as ring laser gyros and fiberoptic inertial measuring units.

Navigation

The required elements for the navigation system include an inertial measuring unit (IMU), a platform alignment device (such as a star scanner or horizon sensor), a global positioning satellite (GPS) receiver/antenna, a microwave landing system, a radar altimeter, and a high resolution air data system. Rendezvous radar and laser docking sensors are used.

Communications and Tracking

This category includes the S-band and L-band transmitters and antennas. Multiband antennas will be used. Communications with the Tracking and Data Relay Satellites (TDRS), orbiting platforms, and ground stations are required.

Instrumentation System

The instrumentation system consists of a health diagnostic network to continuously monitor performance and make projections for future maintenance. The performance monitoring functions include information such as power output of fuel cells per pound of propellant consumed, impulse delivered per pound of propellant, thrust, component temperatures, and any other information required to characterize general health of flight crucial components. In addition, the monitoring system is required to provide advisories as to whether a system shutdown has occurred and to what alternate system the transferred has occurred. Projected time-to-failures on flight crucial equipment is also necessary. The health monitoring system is also called upon to make maintenance schedule projections automatically upon landing or at any time when manually queried.

Data Processing

The data or information processing systems include the computers, mass memories, and multiplexer interface adaptors. Functionally, the processing systems are divided into flight critical and non-flight crucial categories. The flight crucial systems include the adaptive guidance, flight control, navigation, mission sequencing and abort trajectories, power management, and environmental control. Included in the non-crucial systems are the health monitoring system, systems management, and mission control or administration system. The system is expected to be a hierarchal fault-tolerant system with fiber optic data buses and with very large scale integration processing (VLSI) sites. The Fault Detection Isolation and Restructuring (FDIR) system is expected to be auto-activating.

14.0 Environmental Control (ECS)

The environmental control system (ECS) for the winged-body vehicle is designed cool onboard equipment. Many of the components would be similar to those used on the current Space Shuttle. The thermal control for most low-power components will be a heat sink to the winged-body vehicle structure. Radiators located on the payload bay doors and a water-base flash evaporator will be used in conjunction with a fluid coolant loop heat exchanger for the heat rejection requirements of the fuel cells and other high-power devices.

Water for use in the flash evaporator is contained in a storage tank beneath the payload bay. Waste water from the fuel cells is accumulated in the storage tank during flight to reduce initial loading requirements.

15.0 Personnel Provisions

No dedicated personnel provisions required. The transfer of personnel or passengers to orbit will be accommodated by a special personnel canister carried in the payload bay. Thus, this category is zero for all cases considered.

18.0 Payload Provisions

Payload provisions are charged to either the payload canister system or the payload itself. Thus, this category is zero for all cases considered.

19.0 Growth Allowance

A growth allowance of 15 percent of the sum of items 1.0 through 18.0 is added to allow for weight growth as the design progresses to the manufacturing stage.

20.0 Personnel And Gear

Personnel and accessories are carried in a specially designed payload canister and are charged to the payload. Thus, this category is zero for all cases considered.

21.0 Payload Accommodations

Payload accommodations are charged to either the payload canister system or the payload itself. Thus, this category is zero for all cases considered.

22.0 Payload

The payload is the actual useful cargo destined for orbit or return. It does not include the payload canister system and canister-related support equipment. Specific airborne support equipment required by the payload is, however, charged to the payload weight.

23.0 Residual Fluids

Residual fluids are those trapped in lines or tanks or elsewhere which are not usable. Included are liquid and gaseous ascent propellants, hydrogen and oxygen propellants for the OMS and RCS systems, and subsystem fluids such as fuel cell reactants and flash evaporator water (H2, O2, H2O), plus small amounts of trapped pressurant and purge gases.

25.0 Reserve Fluids

Ascent reserves of propellants are calculated based on one percent of the total ΔV requirement. For the winged-body vehicle this allocation is 320 ft/sec. Reserve propellants are also carried by the OMS and RCS systems to account for dispersions from a nominal mission sequence. The propellant reserve for the OMS system is based on an additional 40 ft/sec OMS ΔV on orbit. The propellant reserve for the RCS system is based on a total additional RCS ΔV of 45 ft/sec on orbit split between the forward and aft mounted RCS.

26.0 Inflight Losses

Inflight losses include vented ascent propellants, water from the flash evaporators and fuel cells which is dumped overboard during flight, and vented helium purge gas. Separate calculations are made for fuel cell reactants, evaporator water supply, and helium purge gases.

27.0 Main Propellant

The main propellants are normal boiling point liquid hydrogen and liquid oxygen. The ascent propellant load is that actually consumed by the winged-body vehicle from launch until main engine cutoff, at the required orbit insertion velocity.

The vehicle main engines are run up and checked prior to liftoff. The main engines are drawing propellants from the main tanks during this process. The propellants required for this are calculated as prelaunch losses and are utilized in sizing the volume of the propellant tanks. The prelaunch loss propellants are calculated on the basis of four effective seconds of main engine firing at liftoff (sea level) thrust.

28.0 RCS Propellant

The on-orbit RCS propellants are calculated on the basis of a ΔV of 110 ft/sec.This is split between the forward and aft RCS.

An allowance for RCS entry propellant is budgeted for the entry sequence. It is calculated based on an assumption of a ΔV of 40 ft/sec and is split between the forward and aft RCS.

29.0 OMS Propellant

The OMS propellant is calculated on the basis of the ΔV requirement of 1100 ft/sec for all orbital maneuvers associated with the mission. DRM-1 to deliver payloads to the International Space Station at a 220-nmi altitude.

The OMS ΔV budget is broken down as:

Transfer to 220 nmi	303 ft/sec
Circularization maneuver	210 ft/sec
Maneuvers for prox ops	100 ft/sec
Deorbit from 220 nmi	392 ft/ sec

plus approximately 10 % additional ΔV to account for non-ideal ΔV burns, thrust vector losses, and added margins.

Appendix B: WB-003 Level III Weight Statement Based on the CONSIZ Program

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April 1998

WEIGHT STATEMENT - LEVEL III

wb-003f, gr-ep lh2, rs-2100 - 25 klb p/l, 51.6 deg incl.

	WEIGHT (lb) LEVEL III	II	I	WT. FRACTION OF DRY WT.	SCALING EXPONENT, LENGTH BASED
1.0 Wing			21538.	0.10	2.30
Exposed wing surface		15966.		0.07	2.23
Carry-through		3235.		0.02	2.85
Wing-body fairing		2337.		0.01	2.00
2.0 Tail			2708.	0.01	2.18
3.0 Body			66665.	0.31	2.38
LH2 tank		21474.		0.10	2.87
Structure	18668.			0.09	3.00
Insulation	2806.			0.01	2.00
LO2 tank		14511.		0.07	2.93
Structure	13392.			0.06	3.00
Insulation	1119.			0.01	2.00
Basic and secondary structure		30681.		0.14	1.77
Nose section	2645.			0.01	2.00
Intertank	7947.			0.04	2.00
Aft body/engine fairings	1966.			0.01	2.00
Thrust structure cone	7654.			0.04	2.89
Crew cabin, work station	0.			0.00	0.00
P/L bay doors & hardware	1595.			0.01	0.00
P/L bay support str.	2000.			0.01	0.00
P/L container	2491.			0.01	0.00
Base closeout str.	570.			0.00	2.00
Body flap	2997.			0.01	2.00
Aft OMS/RCS pod str.	816.			0.00	0.00

4.0 Induced environment protection			27047.	0.13	1.87
TPS		25070.		0.12	2.00
Fuselage	17144.			0.08	2.00
Wing & fins	7926.			0.04	2.00
Internal insulation		1004.		0.00	0.00
Nose	233.			0.00	0.00
Payload bay doors	121.			0.00	0.00
Equipment bays	650.			0.00	0.00
Purge, vent, drn, & hazrd gas det		974.		0.00	0.32
5.0 Undercarriage and aux. systems			8158.	0.04	1.64
Nose gear		1267.		0.01	1.74
Running gear	241.			0.00	1.39
Structure	933.			0.00	1.83
Controls	94.			0.00	1.73
Main gear		6890.		0.03	1.63
Running gear	2947.			0.01	1.39
Structure	3554.			0.02	1.83
Controls	390.			0.00	1.62
6.0 Propulsion, main			61340.	0.29	2.90
Engines		41930.		0.20	2.89
Feed system		11363.		0.05	2.89
Pressurization system		718.		0.00	3.89
Gimbal actuation		3247.		0.02	2.89
Eng mounted heat shld		1443.		0.01	2.89
Helium pnuematic & purge system		2638.		0.01	2.89
7.0 Propulsion, reaction control (RCS)			4520.	0.02	1.56
Thrusters and supports		588.		0.00	2.08
Fwd	55.			0.00	2.08
Aft	533.			0.00	2.08
Propellant tanks		1580.		0.01	1.90
Distribution & recirculation		2352.		0.01	1.20
Lines, manifolds, & regulators	1915.			0.01	1.00
Valves	426.			0.00	2.08
Electric pumps	12.			0.00	1.00
Pressurization (included in OMS)		0.		0.00	0.00

8.0	Propulsion, orbital maneuver (OMS)			2869.	0.01	2.07
	Engines		633.		0.00	2.08
	Propellant tanks		883.		0.00	2.07
	Pressurization and feed		1353.		0.01	2.06
	Helium tanks	1118.			0.01	2.05
	Lines (included in RCS)	0.			0.00	0.00
	Valves	235.			0.00	2.08
9.0	Prime power			3054.	0.01	1.53
	Fuel cell system		3054.		0.01	1.53
	Cells	1618.			0.01	2.89
	Reactant dewars	1436.			0.01	0.00
10.0	Electric conversion and distr.			7835.	0.04	0.94
	Power conversion and distr.		1705.		0.01	0.00
	Circuitry		4946.		0.02	0.62
	Elect. pwr dist & cntrl	1459.			0.01	0.61
	Avionic cabling	2425.			0.01	0.61
	RCS cabling	124.			0.00	1.00
	OMS cabling	210.			0.00	0.61
	Connector plates	220.			0.00	0.61
	Wire trays	509.			0.00	0.61
	Electromech. act. (EMA) cabling		1184.		0.01	3.62
11.0	Hydraulic conversion and distr.			0.	0.00	0.00
12.0	Control surface actuation			3479.	0.02	1.91
	Elevons		1302.		0.01	1.91
	Tip fins		540		0.00	1.91
	Body flap		1637.		0.01	1.91
13.0	Avionics			1314.	0.01	0.00
	Guid., nav., & contrl.		248.		0.00	0.00
	Comm. & tracking		377.		0.00	0.00
	Displays & contrl.		0.		0.00	0.00
	Instrum. system		361.		0.00	0.00
	Data processing		328.		0.00	0.00
14.0	Environmental control			2561.	0.01	0.57
	Personnel system		0.		0.00	0.00
	Equipment cooling		559.		0.00	0.00
	Heat transport loop		1451.		0.01	1.00
	Heat rejection system		551.		0.00	0.00
	Radiators	326.			0.00	0.00
	Flash evaporator system	225.			0.00	0.00
15.0	Personnel provisions			0.	0.00	0.00
	Food, waste, & water mngmt.		0.		0.00	0.00
	Seats		0.		0.00	0.00
16.0	Range safety			0.	0.00	0.00

17.0 Ballast			0.	0.00	0.00
18.0 Payload provisions			0.	0.00	0.00
EMPTY			213087.	1.00	2.29
19.0 Growth allowance			31963.	0.00	2.29
EMPTY w/growth			245051.	0.00	2.29
20.0 Personnel			0.	0.00	0.00
Crew & gear		0.		0.00	0.00
Accessories		0.		0.00	0.00
21.0 Payload accomodations			0.	0.00	0.00
22.0 Payload			25000.	0.00	0.00
23.0 Residual and unusable fluids			5572.	0.00	2.47
Main prop. sys. pressurant		2848.		0.00	3.00
OMS		1165.		0.00	1.91
RCS		777.		0.00	1.91
Subsystems		783.		0.00	1.91
25.0 Reserve fluids			9004.	0.00	2.04
Ascent		7180.		0.00	2.07
LH2	909.			0.00	2.07
LO2	6271.			0.00	2.07
OMS		817.		0.00	1.91
RCS		1007.		0.00	1.91
26.0 Inflight losses			13373.	0.00	2.05
Vented ascent propellant		9213.		0.00	2.94
Fuel cell reactants		1612.		0.00	0.00
Evaporator water supply		2427.		0.00	0.00
Helium supply		121.		0.00	2.89
27.0 Propellant, main			2340887.	0.00	3.00
Start-up		32908.		0.00	2.88
LH2	4166.			0.00	2.89
LO2	28742.			0.00	2.88
Ascent		2307980.		0.00	3.01
LH2	292190.			0.00	3.01
LO2	2015789.			0.00	3.01

28.0 Propellant, reaction control		3639.	0.00	1.90
Orbital propellant	2736.		0.00	1.92
Entry propellant	903.		0.00	1.85
29.0 Propellant, orbital maneuver		21750.	0.00	2.06
100nmi alt. circularization prop.	2111.		0.00	2.08
220nmi alt. transfer/circ. prop.	9324.		0.00	2.05
Space station approach propellant	2167.		0.00	2.05
Deorbit propellant	8148.		0.00	2.08
PRELAUNCH GROSS		2664275.	0.00	2.89
		0.	0.00	0.00
Prelaunch gross		2664275.	0.00	2.89
Start-up losses		-32908.	0.00	2.88
LH2	-4166.		0.00	2.88
LO2	-28742.		0.00	2.88
Gross lift-off		2631368.	0.00	2.89
Ascent propellant		-2307980.	0.00	3.01
LH2	-292190.		0.00	3.01
LO2	-2015789.		0.00	3.01
Insertion (50X100 nmi orbit)		323388.	0.00	2.08
Ascent reserves		-7180.	0.00	2.06
LH2	-909.		0.00	2.07
LO2	-6271.		0.00	2.06
OMS propellant - burn 1		-2111.	0.00	2.07
Insertion (100 nmi circular orbit)		314098.	0.00	2.08
Vented ascent propellant		-9213.	0.00	2.93
OMS propellant - burns 2 & 3		-9324.	0.00	2.04
Insertion (220 nmi circular orbit)		295561.	0.00	2.05
OMS propellant - station approach		-2167.	0.00	2.04
RCS propellant		-2736.	0.00	1.91
Payload delivered		-25000.	0.00	0.00
Payload accepted		25000.	0.00	0.00
Fuel cell reactants		-1612.	0.00	0.00
Evaporator water supply		-2427.	0.00	0.00
Helium supply		-121.	0.00	2.88
OMS propellant - deorbit		-8148.	0.00	2.07
Entry		278350.	0.00	2.08
RCS prop. (entry)		-903.	0.00	1.84
Buoyancy		-7521.	0.00	3.00
Landed		269926.	0.00	2.06
Payload (returned)		-25000.	0.00	0.00
Landed (p/l out)		244926.	0.00	2.27
Payload accomodations		0.	0.00	0.00

Personnel		0.	0.00	0.00
Crew & gear	0.		0.00	0.00
Accessories	0.		0.00	0.00
Main prop. sys. pressurant		-2848.	0.00	2.99
Subsystem residuals		-783.	0.00	1.90
Aux. propulsion residuals		-1941.	0.00	1.90
OMS	-1165.		0.00	1.90
RCS	-777.		0.00	1.90
Aux. propulsion reserves		-1824.	0.00	1.90
OMS	-817.		0.00	1.90
RCS	-1007.		0.00	1.90
Buoyancy		7521.	0.00	2.99
Empty w/growth		245051.	0.00	2.29
Landed - RTLS abort (max. p/l)		297261.	0.00	1.86
		0.	0.00	0.00

FLUIDS INVENTORY			0.	0.00	0.00
LH2			303436.	0.00	2.99
Main propulsion		298792.		0.00	3.00
Start-up	4166.			0.00	2.88
Ascent	292190.			0.00	3.01
Reserve	909.			0.00	2.06
Residual	1527.			0.00	2.94
OMS		3390.		0.00	2.04
RCS		1085.		0.00	1.90
Fuel cell		170.		0.00	0.00
LO2			2087458.	0.00	2.99
Main propulsion		2061336.		0.00	3.00
Start-up	28742.			0.00	2.88
Ascent	2015789.			0.00	3.01
Reserve	6271.			0.00	2.06
Residual	10534.			0.00	2.94
OMS		20341.		0.00	2.04
RCS		4338.		0.00	1.90
Fuel cell		1442.		0.00	0.00
Evaporator water			2427.	0.00	0.00
Helium			121.	0.00	2.88

* INDICATES WEIGHT IS NOT WITHIN LIMITS OF WEIGHT EQUATION

wb-003f, gr-ep lh2, rs-2100 - 25 klb p/l, 51.6 deg incl.

DESIGN DATA

number of landing gear wheels	10.0000
number of aerosurface actuators	7.0000
number of landing gear actuators	3.0000
number of TVC actuators	14.0000
number of control surfaces	7.0000
number of cryogenic main tanks	2.0000
number of non-cryogenic main tanks	0.0000
number of rcs thrusters	39.0000
number of rcs tanks	2.0000
number of oms engines	2.0000
number of oms tanks	4.0000
number of hydraulic systems	0.0000
number of different avionic subsystems	5.0000
growth allowance fraction	0.1500
payload weight (lb)	25000.0000
additional down-payload (lb.)	25000.0000
payload bay diameter (ft.)	15.0000
payload bay length (ft.)	35.0000
payload volume (cu. ft.)	6185.0000
mission duration (days), max.	5.0000
total electric power (kva)	240.0000
required peak fuel cell power (kw)	240.0000
total cooling capacity (kw)	15.3000
total cooling capacity (btu/hr/1000)	52.2000
oms delta v for tank sizing (ft./sec.)	1100.0000
oms delta v (ft./sec.) - burn 1	91.0000
oms delta v (ft./sec.) - burn 2	212.0000
oms delta v (ft./sec.) - burn 3	210.0000
oms delta v (ft./sec.) - station appr.	100.0000
oms delta v (ft./sec.) - deorbit	392.0000
lift-off t/w	1.2000
main eng. t/w (vacuum)	86.9200
main eng. isp (vacuum)	443.0000
thickness/chord	0.1000
aft dome to end of thrust str. (ft)	10.5000
nose area (ft^2)	2382.6528
body length (ft)	212.9415

body width (ft)	32.7601
body wetted area (ft^2)	19974.3203
body volume (ft^3)	154761.1094
intertank area w/o doors (ft^2)	4845.9785
aft skirt area (ft^2)	1771.4742
base heat shield area (ft^2)	194.8477
Lh2 tank wetted area (ft^2)	9809.9678
Lox tank wetted area (ft^2)	4821.4668
packaging efficiency	0.6400
wing-body fairing area (ft^2)	2337.1794
carry through width (ft)	32.7601
exposed wing root chord (ft)	52.6175
exposed wing taper ratio	0.3247
exposed wing span (ft)	74.0249
exposed wing aspect ratio	2.1240
exposed wing planform area (ft^2)	2579.8855
exposed wing wetted area (ft^2)	5345.5186
cos of sweep of exposed midChord	0.8872
tip fin planform area (ft^2)	375.6300
body flap planform area (ft^2)	837.1476
mass ratio	8.1369

SIZING PARAMETERS

Mass ratio	8.1369
Propellant mass fraction	0.8771
Body length (ft.)	212.9
Wing span (ft.)	106.8
Theoretical wing area (sq. ft.)	4561.2
Wing loading at design wt (psf)	65.2
Wing planform ratio, sexp/sref	0.57
Sensitivity of volume to burnout wt (cu. ft./klb.)	470.4
Burnout weight growth factor (lb/lb)	3.2

	BODY	WING
Total volume (cu. ft.)	154761.	13443.
Tank volume (cu. ft.)	99054.	0.
Fixed volume (cu. ft.)	0.	0.
Tank efficiency factor	0.6400	0.0000
Ullage volume fraction	0.0300	0.0300

PROPELLANT		FRACTION	DENSITY (lb/cu. ft.)	FLUID VOLUME (cu. ft.)	TANK VOLUME (cu. ft.)
lh2		0.1266	4.42	67254.	69334.
lox		0.8734	71.14	28828.	29719.
lox	(Wing)	0.0000	71.14	0.	0.

Appendix C: Manned Module – Mass Properties & Power for Four Crew/5-Day Mission

Prepared by

Ian MacConochie

FDC/NYMA, Inc.

September 1994

Baseline Level I Weights

Series*	Subject	Wt, lb
100-199	Structure	6,106
200-299	Propulsion	None
300-399	Power	2,183
400-499	Avionics	179
500-599	Environmental Control & Protection	1,048
600-699	Special Provisions	1,411
700-799	Auxiliary Systems	30
Margin	15%	1,644
800-899	Personnel & Payload	6,138
900-999	Fluids & Other** Consumables	4,252
	Total Weight	22,991

*Note: The coding used differs from that used elsewhere in the report. This coding is patterned after that used in the marine industries and was used on a trial basis at the time. The Shuttle Coding lists structure first, namely wing, tail, and body but lists induced environmental protection and landing gear before propulsion. There are other differences, the most obvious being the assignment of 100 digits for each principal grouping without decimals.

**Allows for operation of 60% of lockers for the entire 5 day period.

Level III

Series 100-199 **Structure (Kevlar, Nomex, Allum Liner)**

	Wt, lb
Outer Shell	2,652
Interior Hatch & Mech.	123
Docking Hatch & Mech.	210
Blowout Hatches (4)	160
Airlock	599
Docking Provisions	1,000
Floor Beams & Deck	588
Shell Reinforcement & Attach Points	514
Misc.	260
	6,106

Series 200-299 **Propulsion (None)**

Series 300-399 **Power & Distr.**

	Wt, lb
Fuel Cells (2)	452
Power Reactant Storage (2)	1,328
Load Sharing Batt. Set	202
Pyro Control	64
Load Control	50
Bus	20
Interior Lights	22
Airlock Lights	8
Communications	17
Wire Trays	20
	2,183

Series 300-399 **Power Budget**

	Watts
Voice	20
Computer Controller	26
ECLS	
LiOH	12
Air Temp Humidity	75
2 Gas Controller	5
Flash Evaporator	33
Lockers (60% of 60 Lockers @ 100W)	3,600
	3,771

Series 400-499 **Avionics**

	Wt, lb
Panels	8
Ejection Sequencer	24
Wiring	17
Caution & Warning	2
Communications (Unit mikes, etc.)	40
Central Control	15
Mass Memory	40
Pyrotechnics	33
	179

Series 500-599 **Environmental**

	Wt, lb
Protection	
MLI Blanket	348
Fasteners	52
Bulk Insulation	40
Control	
Nitrogen Tanks	235
Fans	42
Heat Exchangers	30
LiOH Storage	91
Plumbing	30
Flash Evaporator	60
Controls	10
Supports	25
2 Gas Control	40
Air Temp & Hum	45
	1,048

Series 600-699 **Special Provisions**

	Wt, lb
Seats (Ejection) 4 crew	752
Furnishings	175
Commode	49
(Ladders, Handholds)	
Water Separator	20
Fire Suppressant	15
Tanks (Water & Waste)	200
Galley	150
Misc.	50
	1,411

Series 700-799 **Auxiliary Systems**

	Wt, lb
Abort Provisions	30
Margin	1,644

Series 800-899 **Personnel & Payload**

	Wt, lb
Personnel	
Personnel (4)	680
Suits, Helmets, & Gloves	480
Survival Kits	96
Parachute Pack Assemblies	424
Personnel Suit Vents	20
Emergency Medical	
Small Suction Apparatus	15
Emergency Supply of drugs	10
Defibrillator Monitor	15
Supplies of IV Fluids (500 mil)	20
Emergency Oxygen	10
Misc.	48
Payload	
60 Lockers @ 60 Lb ea.	3,600
20% Installation	720
	6,138

Series 900-999 **Fluids & Other Consumables (4 Crew for 5 Days)**

	Wt, lb
Food	117
Water	227
Oxygen (Gaseous)	16
Nitrogen (Gaseous – 1 Re-Press)	187
Flash Evap. Water	3,117
Fuel Cell Reactants	588
	4,252

Appendix D: Unit Structural Weights for the Shuttle and the WB-003 Vehicle

Prepared by

Ian MacConochie

FDC/NYMA, Inc.

September 1999

NOTE:

In this appendix for the WB-003 vehicle (Appendix D, Table III), honeycomb sandwich construction has been assumed for the structural shells. However, some of the honeycomb shell models may not be manufacturable if current materials and fabrication technologies are assumed. As alternatives, the weights allocated for two honeycomb sandwich face sheets could be assigned to skin, and the weight allocations for honeycomb assigned to stringers and ring frames.

Cylindrical shells are successfully being manufactured using polyimide-impregnated tapes as windings (Ref. Telecon Paul Hergenrother, Composites Group NASA LaRC Sept. 1999). The tapes, with the resin in the 'green' condition, are overwrapped onto a metallic mandrel. The polyimide composite is then cured by placing it, while still on the mandrel, into a curing oven. When the assembly is heated to cure the resin, the metallic mandrel expands against the overwrap providing the required compacting force. It may be possible to utilize this technique for large cylindrical structures on WB-003-type vehicles, except that the curing would be accomplished in situ while the component is still in the winding machine. Heat for the cure would be supplied by electric heaters backing up the metallic mandrel, or by a gas-fired furnace confined to a large cylindrical tube inserting at the core of the winder. An oven housing could be used consisting of a large shed that is mounted on railroad tracks and rolled into place over the winder.

Engine fairings are also shown as being fabricated from honeycomb. However, these components could be molded using a polyimide and traditional vacuum bag techniques. Of the seven fairings required, five are identical and two very similar in that the latter are the same shape only requiring openings for RCS engines. The commonality of fairing shapes for the seven engines reduces the acquisition cost of these components considerably — hence reducing the life cycle costs for the vehicle by reducing acquisition costs. The fairings could be molded with integral stiffeners. However, honeycomb sandwich construction is notably more durable than skin-stringer configurations in the presence of high acoustic environments, such as those associated with jet or rocket engines. Other options for engine fairings might include formed and brazed titanium, or high nickel steel alloys, in a honeycomb sandwich configuration — the high nickel steel fairings being considerably heavier than either the titanium or polyimide.

Table I. Shuttle Orbiter Structure Characteristics

Structural Element	All-Up Wt,lb	Area, ft^2 (Wetted)	All-Up W/A, lb/ft^2	Basic Structure Wt, lb	Basic Structure W/A, lb/ft^2	Secondary Structure, Hardware, Etc.	Non-Optimum Factor	Non-Opts
Wing	16,233	4,612	3.52	10,278	2.23	5,955	1.58	Landing gear doors elevon support & mechanisms
Tail	2,804	750	3.74	1,978	2.63	826	1.42	Speed brake mechanism & supports
Body Group								
Nose	5,272	1,314	4.01	4,300	3.27	5,527	1.23	Windshield, nose gear, miscellaneous doors (crew cabin not included)
Mid	11,674	2,640	4.42	11,552	4.37	122	1.03	P/L liner, umbilical plates finish (P/L bay doors not included)
Aft Body	8,147	1,467	5.55	7,299	4.98	293	1.12	Base closeout & thrust structure not included
Thrust Structure	3,182	--	--	3,182	--	0	1.00	No non-opts identified
Secondary Structure								
Crew Cabin	6,870	1,068	6.43	4,208	3.94	2,662	1.63	Windshields and airlock
P/L Doors	4,581	1,080	4.24	2,418	2.23	2,163	1.90	Linkages, winches, hinges & seals
P/L Supports	372	--	--	372	--	--	1.00	None identified
P/L Containers	--	--	--	--	--	--	--	--
Base Close-Out	1,022	294	3.48	1,022	3.98	--	1.00	None identified
Body Flap	456	296	1.54	456	1.54	90	1.00	None identified
AFT/OMS/RCS	2,979	--	--	2,979	--	--	1.00	--
FWD/OMS/RCS	385	--	--	385	--	--	1.00	--

Table II. Shuttle External Tank Structure Characteristics

Structural Element	All-Up Wt,lb	Area, ft^2 (Wetted)	All-Up W/A, lb/ft^2	Basic Structure Wt, lb	Basic Structure W/A, lb/ft^2	Secondary Structure, Wt, lb	Non-Optimum Factor	Non-Opts
LH Tank	31,751	8,588	3.70	31,751	3.70	0	1.00	None identi-fied
LOX Tank	12,555	3,758	3.34	9,900	2.63	2,655	1.27	Slosh baffles
Intertank	13,180	1,946	6.92	10,334	5.31	3,146	1.28	SRB & ET attach fittings

Table III. WB-003 Honeycomb Sandwich Panel Modelling

						Face Sheets				Core						
Structural Element	CONSIZ All-Up Wt. Allocation, lb	Wetted Area, ft^2	All-Up W/A (CONSIZ), lb/ft^2	N. O. F.	Basic Structure W/A, lb/ft^2	Type of Material	No. of Plies	Th/Ply	2 Face Sheets Wt, lb/ft^2	Type of Material	Density, lb/ft^3	Thickness, in	lb/ft^2	Core Bond Allowance, lb/ft^2	Misc. Structure	Basic Honeycomb Structure Model, lb/ft^2
Wing																
Exposed	15,966	5,346	3.0*	1.3	2.31	GrPi	9	.006	0.85*	Pi/G	4.0	3.2	1.06*	0.06	0.34	2.31
Ca-Thru	3,235	1,664	1.9	1.0	1.90	--	--	--	--	--	--	--	--	--		--
W-Bd-Fairing	2,337	2,337	1.0	1.0	1.00	GrEp	5	.006	0.48	Pa/C	4.0	0.8	0.27	0.06	0.19	1.00
Tail	2,708	1,120**	2.4	1.2	2.00	molded	ACC	--	--	--	--	--	--	--	--	2.00
Body																
LH Tank																
Structure	18,668	9,810	1.9	1.1	1.73	GrEp	7	.006	0.665	Pi/G	4.0	2.4	0.80	0.06	0.20	1.73
Insulation	2,806	9,810	0.3	1.0	0.30	--	--	--	--	--	3.1	01.1	--	--	--	0.30
LOX Tank																
Structure	13,392	4,822	2.8	1.1	2.55	NA	tank		AL-Li	skin/stringer & ring frames				--	--	NA
Insulation	1,119	4,822	0.23	1.0	0.23	--	--	--	--	--	3.1	0.9	--	--	--	0.23
Basic Structure																
Nose Cap	300	50	6.0	1.0	6.00	nose cap molded ACC			--	--	-	--	--	--	--	NA
Nose	2,345	2,333	0.90	1.2	0.75	GrPi	4	.006	0.380	Pi/G	4.0	0.8	0.26	0.06	0.07	0.78
Intertank	7,947	4,846	1.64	1.3	1.37	GrPi	7	.006	0.665	Pi/G	4.0	1.63	0.55	0.06	0.09	1.37
Engine Fairing	1,966	1,772	1.11	1.2	0.93	GrPi	5	006	0.473	Pi/G	4.0	1.0	0.34	0.06	0.06	0.94
Thrust Cone	7,654	NA	NA	1.6	NA	GrPi	28	.006	NA	Pi/G	6.5	NA	NA	0.06	NA	NA
Secondary Structure																
Crew Cab	None required															
P/L Doors	1,595	630	2.53	2.0	1.27	GrEp	7	.006	0.65	Pa/C	4.0	1.5	0.50	0.06	0.06	1.27
P/L Bay	2,000	NA	NA	NA	--	--	--	--	--	--	--	--	--	--	--	--
P/L Containers	2,491	NA	NA	NA	--	--	--	--	--	--	--	--	--	--	--	--
Base Close-Out	978	388	2.52	1.1	2.29	GrPc	12	.006	1.14	Pi/G	4.0	2.8	0.94	0.06	0.15	2.29
Body Flap	2,997	1,758	1.71	1.1	1.55	ACC molded panels										
Aft OMS/RCS	816	NA	NA		NA	GrEp Misc.brackets & tank supports, OMS and RCS thrust structure										

*Average value for tapered wing covers

**Wetted Area of Two Fins

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE February 2002	3. REPORT TYPE AND DATES COVERED Contractor Report	
4. TITLE AND SUBTITLE Characterization of Subsystems for a WB-003 Single Stage Shuttle			5. FUNDING NUMBERS NAS1-96013 WU 242-33-01-50
6. AUTHOR(S) Ian O. MacConochie			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) FDC/NYMA, Inc. Langley Research Center Hampton, VA 23681			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Langley Research Center Hampton, VA 23681-2199			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/CR-2002-211249
11. SUPPLEMENTARY NOTES Langley Technical Monitor: Roger A. Lepsch, Jr.			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified–Unlimited Subject Category 18 Distribution: Nonstandard Availability: NASA CASI (301) 621-0390			12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Subsystems for an all oxygen-hydrogen-single-stage shuttle are characterized for a vehicle designated WB-003. Features of the vehicle include all-electric actuation, fiber optics for information circuitry, fuel cells for power generation, and extensive use of composites for structure. The vehicle is sized for the delivery of a 25,000 lb. payload to a space station orbit without crew. When crew are being delivered, they are carried in a module in the payload bay with escape and manual override capabilities. The underlying reason for undertaking this task is to provide a framework for the study of the operations costs of the newer shuttles.

14. SUBJECT TERMS Shuttle; Single stage; All oxygen-hydrogen; Subsystem characterization			15. NUMBER OF PAGES 94 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL